Modeling Ablation of Laminated Composites: A Novel Manual Mesh Moving Finite Element Analysis Procedure with ABAQUS

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Abstract

The recent improvements of the commercial, general purpose Finite Element Analysis (FEA) software have allowed them to be used for modeling ablation problems. ABAQUS for example, provides a user-subroutine UMESHMOTION along with the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm that enable the users to couple the heat transfer with the progressive surface recession (i.e., ablation). However, such a numerical capability is limited to model ablation problems when the ablation front (i.e., receding surface) is confined within a single material domain (e.g., homogenous material). For ablation problems when the ablation front proceeds from one material domain to another (e.g., laminated composite materials that consist of multiple laminate layers with different material orientations), such a numerical

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capability is insufficient, since the mesh is not allowed to flow from one material domain to another when the UMESHMOTION subroutine is used. In this paper, a novel computational procedure that sequentially performs the general heat transfer analysis and the general static analysis in ABAQUS, is proposed enabling the capability of ABAQUS for modeling ablation of laminated composites. The proposed procedure is verified by comparing the predictions of temperature and ablation histories of a two-dimensional isotropic panel (i.e., with single material domain) with those obtained using the traditional UMESHMOTION+ALE method. In addition, a case study of applying the proposed procedure to predict the thermal and ablation response of a laminated carbon fiber reinforced epoxy matrix (CFRP) composite panel subjected to a high-intensity and short-duration radiative heat flux is demonstrated.

Keywords: Laminated composite materials; Ablation; Material moving front; Mesh moving procedure; Finite element analysis (FEA)

1. Introduction

Laminated composite materials experience surface material removal (i.e., ablation) due to oxidation, nitridation, and vaporization when exposed to extreme heating conditions such as during lightning strike [1-3], laser machining process [4], and hypersonic reentry [5]. Although the thermal and ablative response of the laminated composite materials have been identified and characterized in some experimental studies [5, 6], developing an accurate predictive model is still lagging behind due to the tight coupling between the heat conduction and the progressive

surface material removal. In particular, a moving boundary condition due to the progressive material removal needs to be considered in the formulation of the heat conduction problem. One of the prevalent approach to develop such models is to use the commercial, general purpose finite element analysis software ABAQUS with the user-subroutine UMESHMOTION and the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm (UMESHMOTION+ALE method) [7]. However, when using the UMESHMOTION subroutine, the mesh is not allowed to flow from one material domain to another, and hence, such a method is not applicable for predicting the ablation of laminated composite materials, for which the material may recede from one layer to another (with different material orientations) during ablation. To enable ABAQUS with the capability of modeling ablation for laminated composites, in this paper, we propose a novel computational procedure, which performs the heat transfer analysis and the general static analysis in parallel and solves the temperature and ablation depth sequentially after every a few time increments. Here, we present the verifications for the proposed computational procedure by comparing the predictions of the recession and temperature histories of a two-dimensional (2D) homogenous isotropic panel with those predicted using the existing UMESHMOTION + ALE method. Note that, the choice of an isotropic panel allows us to use the UMESHMOTION + ALE method. Finally, a case study is presented to demonstrate the application of the proposed computational procedure to the prediction of the thermal and ablation response of a laminated carbon fiber reinforced epoxy matrix (CFRP) composite panel subjected to a high-intensity short-duration radiative heat flux. Note that, for such a case, the traditional UMESHMOTION + ALE method is not applicable.

2. Heat Transfer Equations Considering Material Surface Removal

The heat conduction in solid materials considering the material surface removal is typically governed by the following equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} - \dot{s} \frac{\partial T}{\partial z} \right) - \nabla \cdot (k \nabla T) = \dot{q} \quad (1)$$

where ρ is the density, C_p is the specific heat, T is the temperature, t is time, $\dot{s}$ is the surface recession rate, z is the coordinate normal to the recession surface (i.e., for ablation problems when surface recedes in the through-the-thickness direction), k is the thermal conductivity, and $\dot{q}$ is the rate of energy input (e.g., from laser or plasma irradiation or aerodynamic convection). Here, the surface recession rates $\dot{s}$ (i.e., the ablation rate) of the solid material under extreme irradiation and convection heating conditions are strongly related to various chemical reactions that can occur on the surface of the material. Those possible reactions include evaporation, sublimation, oxidation, as well as nitridation. The surface recession rate is often determined through either experimental tests or theoretical predictions. For example, the ablation rate of the Thermal Protection System (TPS) material under hypersonic re-entry conditions is obtained through the Arc Jet test [8]. However, such experimental tests are restricted and the availability of the experimental data is quite limited. Meanwhile, a few gas-surface predictive models have been proposed to predict the mass fractions of the ablation products and, thus, the ablation rate of the TPS material [9-11]. Another typical example of the heat conduction problem with progressive material removal is the pulsed laser ablation (PLA) of solid materials [12]. Such a problem is quite common in the applications include laser surface processing and laser machining. In the case of PLA, the ablation mechanisms usually consist of two stages: the rapid

material evaporation stage under low laser fluence conditions and the material phase explosion stage under high laser fluence conditions [12]. The ablation rate of solid materials during the evaporation stage is typically expressed using the Hertz-Knudson equation:

$$\dot{s} = \beta \sqrt{\frac{m}{2\pi k_B T}} \frac{P_b}{\rho} \exp \left[\frac{m L_v}{k_B} \left(\frac{1}{T_b} - \frac{1}{T} \right) \right], \quad (2)$$

where β is the vaporization coefficient, m is the atomic mass of the solid material, k_B is the Boltzmann constant, L_v is the latent heat of vaporization of the material, and T_b and P_b are the boiling temperature and the boiling pressure, respectively.

The material removal during the material phase explosion stage of PLA is quite complicated and no available explicit expressions are available to predict the ablation rate to the authors' best knowledge. The determination of such ablation rates during material phase explosion still typically relies on extensive experimental tests. Generally, for common solid materials, the surface recession rate is dependent on the enthalpy of the material, temperature, and pressure [9-11]. In the case of laminated solid materials, the surface recession rate may also depend on the material orientations of the laminate layers. In other words, the surface recession rate may also vary, when the material recedes from one laminate layer to another (assuming the material orientations of those layers are different).

3. Numerical Implementation

Numerically, traditional methods to model ablation problems utilize moving grid systems with finite difference (or volume) analysis, which allow to predict the ablation and temperature

histories by considering the coupling between the heat conduction and the progressive material removal. However, the ablation analysis tools developed based on these methods are often restricted, such as the Fully Implicit Ablation and Thermal Analysis (FIAT) tool developed by NASA Ames [8]. Moreover, the capability of such codes for modeling ablation of laminated composite materials, for which the ablation front may develop from one laminate layer to another (with different material orientations), has barely been reported. In addition to the existing approach with finite difference (or volume) method, the recent improvements of the commercial, general purpose Finite Element Analysis (FEA) software, have also allowed them to be used for modeling ablation problems considering the progressive material removal. ABAQUS for example, allows the users to model ablation problems for homogenous materials (i.e., ablation front is confined within a single material domain) using a provided user subroutine and the remeshing algorithm. However, this approach is not applicable to model ablation problems for laminated composite materials. To overcome this limitation, in this paper, a novel computational procedure based on a manual mesh moving (MMM) approach is proposed to model ablation for laminated composite materials in ABAQUS. The detailed procedures of the traditional UMESHMOTION+ALE approach (for modeling ablation of homogenous materials) and the proposed MMM approach (for modeling ablation of both homogenous and laminated composite materials) are discussed in Sections 3.1 and 3.2, respectively.

3.1. Traditional Mesh Moving Method with Adaptive Remeshing Algorithm in ABAQUS

The commercial, general purpose FEA software, ABAQUS, provides a user subroutine UMESHMOTION and the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm, that

enables the users to model ablation problems by coupling the general heat transfer analysis with the progressive surface material removal. In particular, the surface recession rate of the material can be prescribed in the UMESHMOTION subroutine as a function of surface temperature or time. After each time increment, the UMESHMOTION subroutine is used to calculate the corresponding ablation depth,

$$\Delta h = \int_{t_1}^{t_1 + \Delta t} \dot{s} dt, \quad (3)$$

where t_1 is the time at the end of the previous time increment and Δt is the current time increment. Meanwhile, the surface nodes are moved to their new locations according to the calculated ablation depth. Next, the ALE remesh algorithm generates the new mesh after the surface nodes are moved to their new locations. Note that, the boundary conditions (e.g., surface heat flux) can also be automatically updated. This UMESHMOTION+ALE method has been recently used in Ref. [13] for the analysis of ultrashort pulse laser-material interaction and in Ref. [14] for modeling ablative behavior and thermal response of carbon/carbon composites. Meanwhile, such a method has also been validated for PLA of aluminum under the low laser fluence regime [15]. However, as mentioned previously, this method is not applicable when the ablation problem includes multiple material domains (e.g., laminated composite materials, which are showing promising applications in the aerospace industry) due to the fact that ABAQUS does not allow mesh to flow from one material domain to another. Therefore, in the case when the material recedes from one layer to another layer with different orientations, the analysis will be terminated due to severely distorted mesh near the boundary of the two layers.

3.2. Proposed Manual Mesh Moving (MMM) FEA Procedure with ABAQUS

To model ablation for laminated composite materials. Here, we propose a MMM FEA procedure, which consists of a general heat transfer step and a general static step in ABAQUS. In this procedure, the temperature solution after each time increment is obtained from the general heat transfer step and further used to calculate the ablation depth (see (5)) using a USDFLD (or URDFIL) subroutine. After n time increments (i.e., from time increment i to time increment $n+i-1$, where $i=1, 2, 3 \dots$), the accumulated ablation depth is calculated using the trapezoidal rule:

$$h \approx \frac{1}{2} \sum_{k=i}^{n+i-2} (t_{k+1} - t_k) (\dot{s}|_{t_{k+1}} + \dot{s}|_{t_k}), \quad (4)$$

where the recession rate $\dot{s}$ can be either a function of time or surface temperature. If the accumulated ablation depth reaches a certain prescribed tolerance, $h > Tol$ (the effects of the tolerance on the numerical accuracy are discussed in Section 4.2), then the general heat transfer analysis is terminated using the LSTOP flag in the URDFIL subroutine. Next, the obtained accumulated ablation depth, h , is applied as a displacement boundary condition using a DISP subroutine in a separate general static analysis. The deformed mesh subjected to the displacement boundary condition is obtained after performing the general static step (i.e., to get the new mesh after the surface material removal). After that, the temperature from the previous mesh (i.e., mesh used in the heat transfer analysis) is mapped to the deformed mesh and further used as an initial temperature boundary condition in the subsequent heat transfer analysis. Here, it should be noted that the temperature distribution is mapped from domain to domain (not from node to node) and only the temperature distribution within the domain excluding the ablated area from the previous mesh is mapped to the deformed mesh, while the temperature distribution

within the domain of the ablated area from the previous mesh is disregarded due to the removal of materials. Hence, the mapping of the temperature distribution automatically accounts for the thermal energy carried away by the removed materials. This computational procedure repeats until the end of the analysis. Figure 1 shows the schematic diagram of the proposed MMM FEA procedure. Note that since the above two steps are separately performed, a set of MATLAB scripts has also been developed to enable the data transfer (e.g., temperature solution, accumulated ablation depth) between the two steps and enable the automatic sequential implementation. It is worth emphasizing that, since the remeshing is achieved using a separate general static step, the mesh is permitted to flow from one material domain to another and, thus, the proposed procedure enables us to model ablation for laminated composite materials.

Fig. 1. Schematic diagram of the proposed MMM FEA procedure with ABAQUS.

4. Verification of the Proposed MMM FEA Procedure

To verify the proposed MMM FEA procedure in ABAQUS (see the schematic diagram in Fig. 1), we consider a simple ablation problem with a 2D isotropic square panel (10×10 mm). By considering an isotropic material allows us to obtain the temperature and ablation predictions using the traditional UMESHMOTION+ALE method. Meanwhile, the problem is also solved using the proposed MMM FEA procedure. Here, the proposed MMM FEA procedure is considered verified if the temperature and ablation predictions obtained from the proposed MMM FEA procedure agree well with those obtained using the traditional UMESHMOTION+ALE method.

For this verification problem, the 2D isotropic square panel is subjected to a uniform heat flux, 350 W/m^2 , on top of the panel, for a duration of $50 \text{ }\mu\text{s}$. The problem setup is shown in Fig. 2. The thermal conductivity of the material is $6.578 \times 10^{-4} \text{ W/m}\cdot^\circ\text{C}$, the specific heat is $1004.3 \text{ J/kg}\cdot^\circ\text{C}$, and the density is $1.814 \times 10^{-6} \text{ kg/m}^3$. It is worth mentioning that for real ablation problems, the thermal conductivity, specific heat, and density as well as many other material properties are temperature and pressure-dependent. For the purpose of the code verification, these relevant material properties are assumed to be temperature-independent. Here, the density is assumed to be a constant. In other words, the density variation and heat loss due to possible material decomposition are not considered in this verification study.

Fig. 2. Setup of the verification problem.

The recession rate for this verification problem is prescribed and assumed to be a nonlinear function of time, written as:

$$\dot{s} = -308e^{-1.5 \times 10^5(t - 2.5 \times 10^{-6})} + 100, \quad t \geq 10 \mu\text{s}, \quad (5)$$

where t is time in s, and $\dot{s}$ is the prescribed surface recession rate in m/s. It should be mentioned that such a prescribed recession rate does not represent the ablative behavior of any particular materials, it is only used here for code verification purposes. In addition, the choice of a nonlinear recession rate also helps to eliminate the effects of linear simplifications on the verification and, thus, enhances the quality of the code verification.

4.1. Comparison of temperature and ablation results

The ablation history on the surface (i.e., point A in Fig. 2) and the temperature histories at five spatial points (i.e., points A, B, C, D, and E in Fig. 2), as well as the temperature histories in the through-the-thickness direction at different times (i.e., 10, 20 30, 40, and 50 μs) of the considered 2D square panel are predicted using both the traditional UMESHMOTION+ALE method and the proposed MMM FEA procedure (with numerical tolerance, $Tol = 5 \times 10^{-5}$ m, see Fig. 1). The analytical solution of the ablation history is also obtained by taking the integral of (5) over time. The comparisons are shown in Figs. 3-5. As it can be seen that the ablation history predicted using the proposed MMM FEA procedure agrees well with both the analytical solution and the prediction using the UMESHMOTION+ALE method (see Fig. 3). Furthermore, the temperature histories predicted using the proposed MMM FEA procedure also compare

favorably with the predictions using the UMESHMOTION+ALE method (see Figs. 4 and 5).

These verified the proposed MMM FEA procedure such that the procedure can be further applied to predict the ablation and temperature histories for laminated composite materials, for which the traditional UMESHMOTION+ALE method is unable to handle.

Fig. 3. Prediction of the ablation history on the surface of the 2D panel: comparison between the UMESHMOTION+ALE method, the proposed MMM FEA procedure (with $Tol = 5 \times 10^{-5}$ m), and the analytical solution.

Fig. 4. Prediction of temperature histories at five spatial points (i.e., A, B, C, D, and E in Fig. 2): comparison between the UMESHMOTION+ALE method and the proposed MMM FEA procedure (with $Tol = 5 \times 10^{-5}$ m).

Fig. 5. Prediction of temperature profiles across the thickness direction of the 2D panel at five different times (i.e., 10, 20, 30, 40, and 50 μ s): comparison between the UMESHMOTION+ALE method and the proposed MMM FEA procedure (with $Tol = 5 \times 10^{-5}$ m).

4.2. Effects of the tolerance, Tol

During the implementation of the proposed MMM FEA procedure, the tolerance, Tol (see Fig. 1), serves to control the frequency of remeshing the computational domain and updating the heat flux boundary condition. In this section, the effects of this tolerance value, Tol , on the temperature and ablation predictions using the proposed MMM FEA procedure are investigated. In addition to the simulation case described in Section 4.1 using the procedure proposed MMM FEA procedure with a tolerance of $Tol = 5 \times 10^{-5}$ m, two extra simulations were carried out for the same verification problem (see Fig. 2) using the proposed MMM FEA procedure with tolerance values of $Tol = 1 \times 10^{-4}$ and 5×10^{-4} m, respectively. Figure 6 shows the comparisons of the ablation history predicted using the proposed MMM FEA procedure ($Tol = 5 \times 10^{-5}$, 1×10^{-4} , and 5×10^{-4} m) and the ablation history predicted using the traditional UMESHMOTION+ALE method. As one can see, the ablation history predicted from the proposed MMM FEA procedure compares better with the prediction of the traditional UMESHMOTION+ALE method when the tolerance value was decreased from 5×10^{-4} m to 5×10^{-5} m. Moreover, a significant discrepancy can be observed in the beginning of the ablation ($t < 20 \mu s$) when a tolerance value of 5×10^{-4} m was used. Furthermore, Figure 7 shows the comparisons of the temperature history at the spatial point B (see Fig. 2) predicted using the two methods. It is evident that a smaller tolerance could also provide a better match for the temperature predictions. In general, the smaller the tolerance, the more frequently the boundary condition updates, and thus, the more accurate the predictions are. However, using a smaller tolerance could adversely increase the computational time. For example, when the tolerance is decreased from 5×10^{-4} m to 5×10^{-5} m, the computational time is increased from 30 minutes to 120 minutes.

Fig. 6. Effects of tolerance: comparisons of ablation history predictions from the UMESHMOTION+ALE method and the proposed MMM FEA procedure (with $Tol=5\times10^{-5}$, 1×10^{-4} , and 5×10^{-4} m).

Fig. 7. Effects of tolerance: comparisons of temperature history predictions (at point B, see Fig. 2) from the UMESHMOTION+ALE method and the proposed MMM FEA procedure (with $Tol=5\times10^{-5}$, 1×10^{-4} , and 5×10^{-4} m).

5. Case Study: CFRP Composite Laminate Under High-intensity Short-duration

Radiative Heat Flux

In this section, the proposed MMM FEA procedure is applied to predict the ablation and temperature response of a 2D laminated CFRP composite panel, when it is subjected to a high-intensity short-duration radiative heat flux. The CFRP composite panel considered in this case study is an 18-layer laminated panel. The laminate schedule is: [(0/90F)/45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45/(0/90F)]. The thicknesses of the woven and unidirectional layers are 0.195 and 0.130 mm, respectively. The temperature-dependent density, thermal conductivity, and specific heat used in this case study are taken from Ref. [16].

The spatial profile of the radiative heat flux is assumed to follow a Gaussian distribution with a peak irradiation of 5.6 W/mm^2 and a spot size (i.e., radius of the affected zone) of 40 mm. The heat flux is applied for a duration of 0.8 s. Meanwhile, the top surface of the 2D laminated panel is also applied with a radiation boundary condition to the ambient surroundings. The problem setup is shown in Fig. 8.

Fig. 8. Problem setup: an 18-layer CFRP laminated composite panel subjected to a high-intensity short-duration radiative heat flux.

To demonstrate the capability of this proposed FEA procedure, the recession rate of the CFRP composite material is considered to take the finite-rate ablation formulation proposed by Park *et al.* [9-11]. It should be mentioned that the finite-rate ablation formulation is normally used to model ablation when materials are exposed to convective heating environments (e.g., hypersonic reentry), in this case study, due to a lack of information on the surface chemical reaction related parameters (e.g., enthalpy) of the CFRP composites, the finite-rate ablation formulation is used to model ablation under a simple radiative heating environment. Therefore, this case study does not necessarily reflect the real physics, but should be regarded as a demonstration of the modeling capability of this proposed FEA procedure. The accurate determination of the recession rates of the CFRP composite material under various heating conditions is beyond the scope of this study.

According to the Park's finite-rate ablation model, the mass blowing rates, $\dot{m}$, due to various surface-gas reactions (i.e., oxidation, nitridation, and sublimation) are:

$$\dot{m}_1 = \rho_e C_O \bar{v}_O \beta_O \frac{M_C}{M_O}; \quad (C_{(s)} + O \rightarrow CO), \quad (6)$$

$$\dot{m}_2 = 2\rho_e C_{O_2} \bar{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(s)} + O_2 \rightarrow 2CO), \quad (7)$$

$$\dot{m}_3 = \rho_e C_N \bar{v}_N \beta_N \frac{M_C}{M_N}; \quad (C_{(s)} + N \rightarrow CN), \quad (8)$$

$$\dot{m}_4 = \rho_e (C_{C_3,E} - C_{C_3}) \bar{v}_{C_3} \beta_{C_3}; \quad (3C_{(s)} \rightarrow C_3), \quad (9)$$

where ρ_e is the density of the free stream, $\bar{v}_i$ ($i=O, O_2, N$, and C_3) is the mean molecular speed of the various species, and $\bar{v}_i = \sqrt{k_B T_s / 2\pi m_i}$, T_s is the surface temperature, k_B is the Boltzmann constant, and m_i is the mass of the species, β_i is the efficiency of each surface reaction, C_i is the mass fraction of the species, $C_{C_3,E}$ is the equilibrium mass fraction of C_3 , and M_j ($j=C, O, O_2$, and N) is the molecular weight of the species. The corresponding values of these parameters are taken from Refs. [9-11] and listed in Table 1. The total mass blowing rate due to the surface chemical reactions is:

$$\dot{m}_c = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4, \quad (10)$$

Meanwhile, the mass blowing rate due to the liberation of the pyrolysis gases (i.e., the consequence of resin decomposition) is assumed to be proportional to the mass blowing rate due to the surface chemical reactions, and it takes the form:

$$\dot{m}_g = 0.21\dot{m}_c, \quad (11)$$

After the mass blowing rates are determined, the surface recession rate, $\dot{s}$, can be obtained by:

$$\dot{s} = (\dot{m}_c + \dot{m}_g) / \rho_s, \quad (12)$$

where ρ_s is the solid density near the surface.

Table 1. Finite-rate ablation formulation parameters of the CFRP composite material [9-11].

Parameter	Values	Unit
ρ_e	0.003	kg/m ³
ρ_s	1600	kg/m ³
M_C	12.01×10^{-3}	kg/mol
M_O	16.00×10^{-3}	kg/mol
M_{O_2}	32.00×10^{-3}	kg/mol
M_N	14.00×10^{-3}	kg/mol
m_O	2.66×10^{-26}	kg
m_{O_2}	5.31×10^{-26}	kg
m_N	2.32×10^{-26}	kg
m_{C_3}	5.98×10^{-26}	kg
k_B	1.38×10^{-23}	m ² · kg/(s ² · K)
β_O	$0.63 \exp(-1160/T_s)$	-
β_{C_3}	$30.00 \exp(-21490/T_s)$	-
β_N	0.3	-
β_{O_2}	0.5	-
C_O	16.00×10^{-3}	-
C_{O_2}	1.00×10^{-6}	-
C_N	$0.7M_N$	-
C_{C_3}	$5.4M_C$	-
$C_{C_3,E}$	$\frac{1.90 \times 10^9}{3\rho_e T_s M_C} \exp(-59410/T_s)$	-

5.1. Numerical Implementation

The computational domain of the considered 2D CFRP laminated composite panel is 100 mm long (x -direction) and 35 mm thick (z -direction). The domains used in the general heat transfer and the general static analyses are both meshed with the ABAQUS CPE4T elements (i.e., the 4-node plane strain coupled temperature-displacement elements). Note that these two analyses are sequentially performed, and the mesh configuration (e.g., size and number) used in the general static analysis is directly taken from its previous general heat transfer analysis (see the schematic diagram Fig. 1). To balance the accuracy and computational cost, the meshes at the region near the heated surface are refined (with mesh size of 0.25 mm by 0.017 mm) and more coarse mesh is used far away from the heated surface (with mesh size of 0.25 mm by 0.095 mm). The meshing results in a total of 9849 elements. The mesh size used in the current simulation provides sufficient accuracy based on preliminary mesh refinement studies. Moreover, the tolerance (see also Fig. 1) used in the current simulation is $Tol = 0.001$ mm. The computation is performed on a laptop with dual core and 16 GB RAM, and the computational time is around 20 hours.

5.2. Simulation Results and Discussions

The results of the thermal and ablation response of the laminated composite panel under the radiative heat flux are obtained after performing the proposed MMM FEA procedure (with $Tol = 0.001$ mm). The ablation history at the center of the laminated composite panel is provided in Fig. 9, from which it can be observed that two and half of the laminate layers have been

completely consumed during the ablation process with a total ablation depth of around 0.39 mm. Meanwhile, an attempt of using the traditional UMESHMOTION+ALE method to predict the ablation history of the laminated composite panel was also carried out. However, as it can be seen from Fig. 9, the analysis terminated at around 0.40 s when the ablation front approaches near the boundary between layer 1 and layer 2. As explained earlier, the termination of the analysis is because ABAQUS does not permit mesh to flow from one material domain to another when the UMESHMOTION+ALE method is used. In addition, the mesh gets severely distorted when the mesh moves near the boundary between layer 1 and layer 2, which necessarily reduced the numerical accuracy of the solution. As shown in Fig. 9, the discrepancy of the ablation depths predicted using the two methods grows with time until the analysis with the UMESHMOTION+ALE method is terminated. To rule out the possibility that such a discrepancy is caused by an unsatisfactory accuracy of the proposed MMM procedure (rather than the reduced accuracy of the UMESHMOTION+ALE method), two additional simulations with increased and reduced tolerances were carried out ($Tol=0.05$ and 0.0005 mm). The comparison of the ablation histories obtained from these two simulations with those obtained from the original simulation ($Tol= 0.001$ mm) is also provided in Fig. 9. As one can see, the effects of the tolerance on the ablation history are quite insignificant. This hence implies that the discrepancy of the ablation depths predicted using the two methods (i.e., the UMESHMOTION+ALE method and the proposed MMM procedure) could be mostly owing to the reduced numerical accuracy of the UMESHMOTION+ALE method when the mesh gets severely distorted near the boundary of the two laminate layers.

Fig. 9. Ablation depth at the center of the laminated CFRP composite panel versus time: comparison between the UMESHMOTION+ALE method and the proposed MMM FEA procedure (with $Tol = 5 \times 10^{-5}$, 1×10^{-6} , 5×10^{-7} m).

Furthermore, the temperature histories at the center (i.e., $x=0$, see Fig. 8) of the top surface and centers of the bottom of layers 1, 2, 3, and 4 of the laminated CFRP composite panel are shown in Fig. 10. Here, the centers of the bottom of layers 1, 2, 3, and 4 are also denoted as points A, B, C, and D, as shown in Fig. 8. As one can see, the temperature at the receding surface reaches to a constant value of around 4215 °C (see Fig. 10). Also, it can be observed that the first and the second layers are completely consumed at 0.47 and 0.69 s, respectively, when the temperatures at centers of their bottom gradually increase to around 4215 °C. Moreover, Figure 11 captures the history of the mass blowing rate at the center of the top surface. It can be noticed that the mass blowing rate drastically increased to 0.7 kg/(m² · s) from 0.10 to 0.15 s, which also

shows a good correlation with the rapid temperature rise in the beginning of the temperature history (see also Fig. 10).

The ablation profiles of the laminated composite panel at different times (i.e., 0.2, 0.4, 0.6, and 0.8 s) are plotted in Fig. 12. It can be seen that the proposed MMM FEA procedure successfully captures the ablation profiles when the material removal proceeds from the first to the second layer and from the second to the third layer. In addition, Figure 13 illustrates the temperature distributions and shape changes in the right half (i.e., $x > 0$, see Fig. 8) of the laminated composite panel at 0.4 and 0.8 s during the ablation process. Here, it is worth mentioning again that the traditional UMESHMOTION+ALE method is not applicable when the ablation proceeds from one layer to another (with different material orientations), while the proposed MMM FEA procedure overcomes the limitation of the UMESHMOTION+ALE method and enables us to capture the ablation when it proceeds from one layer to another and, thus, it is more advantageous for modeling ablation problems for laminated composite materials.

Fig. 10. Temperature histories at the center of the top surface and at centers of the bottom of the first four layers of the laminated CFRP composite panel.

Fig. 11. History of mass blowing rate at the center of the top surface of the laminated CFRP composite panel.

Fig. 12. Ablation profiles of the laminated CFRP composite panel at 0.2, 0.4, 0.6, and 0.8 s.

Fig. 13. Temperature distributions and shape changes of the laminated CFRP composite panel due to ablation: at (a) 0.4 and (b) 0.8 s.

6. Conclusion

In this paper, a novel computational procedure, based on manual mesh moving (MMM) Finite Element Analysis (FEA), with ABAQUS has been proposed. The procedure enables us to predict the thermal and ablation response for the laminated composite structures that consist of multiple layers with different material orientations. In general, such problems cannot be handled by the existing UMESHMOTION+ALE method that is provided by ABAQUS, since the UMESHMOTION subroutine does not allow mesh to flow from one laminate layer to another (with different material orientations). The proposed MMM FEA procedure has been verified by comparing the predictions of the temperature and ablation histories of a 2D isotropic material (i.e., with single material domain) with those predicted using the traditional UMESHMOTION+ALE method (i.e., a validated method for homogenous solid materials). In addition, the effects of the tolerance, Tol , during the implementation of the proposed MMM procedure on the model predictions have also been investigated. Results suggest that a smaller tolerance can yield a better match to the results predicted using the traditional UMESHMOTION+ALE method, but will lead to a considerable increase of computational time. Finally, a case study has been presented to demonstrate a successful application of the proposed MMM FEA procedure to predict the thermal and ablation response of a laminated CFRP composite panel under a high-intensity short-duration radiative heat flux. Note that the validation of the proposed procedure against experimental data will be a subject of our future research (the experimental data on the ablation of laminated composite materials, such as the ablation rates, ablation and temperature response, are currently not available in the literature). Furthermore, the

proposed MMM FEA procedure can be applied to predict the thermal and ablation response of laminated composites subjected to pulsed laser and lightning strike exposures.

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