OUT-OF-PLANE DEFORMATION OF CARBON-FIBER-REINFORCED-POLYMER WITH LOCAL DAMAGE UNDER RAPID HEATING

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Abstract
CFRP which consists of carbon fiber/phenol resin is widely used for a thermal protection system in Aerospace field. Rapid-heating-induced thermal deformation of CFRP is measured using digital image correlation (DIC) technique in the present study. Specimen temperature is above 1200K so that long wavelength radiation is significant and the DIC technique is not easy to apply. A heat resistance random pattern on the specimen surface, which is made by ceramic materials, and optical filter allow to apply the DIC method. A complicated deformation including rapid-heat transfer and simultaneously occurring CFRP ablation is measured transitionally. Based on these experimental results, we perform the multi-physics modeling which includes chemical and mechanical effects.

1. Introduction

The carbon fiber reinforced plastic (CFRP),which consists of carbon fiber and phenol resins, is widely used for thermal protection systems (TPS) in the field of aerospace such as rocket engine nozzle and nose cone of re-entry vehicle. This material is generally called ablator. When the ablator is heated, pyrolysis occurs and consumes the thermal energy simultaneously, thereby reducing the thermal

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conduction. Ablators are usually heated rapidly in inert atmosphere around 1000°C ~ 3000°C according to the usage environment. A number of studies have reported the oxidation behavior of ablator under rapid heating [1, 2]. Meanwhile, the thermal deformation behavior under rapid heating has not been estimated. This behavior includes not only the linear thermal expansion, but also the irrecoverable deformation such as the shrinkage due to pyrolysis and internal damage from increasing thermal stress.

In this study, experimental devices are developed and discussed; these devices can rapidly heat to measure local and irrecoverable deformation of CFRP by Stereo DIC method. Here we report the results of trial test employing hand-lay-up CFRP coupon specimen and analytical procedure.

2. Rapid heating test

2.1. Infrared (IR) lamp rapid heating system

In the first step, experimental devices are developed (Figure 1); these devices can rapidly heat to reproduce irrecoverable deformation of CFRP. The rapid heating system has observation windows at 45° intervals. Near the observation windows, gas exhaust nozzles emit N_2 gas to reduce contamination.

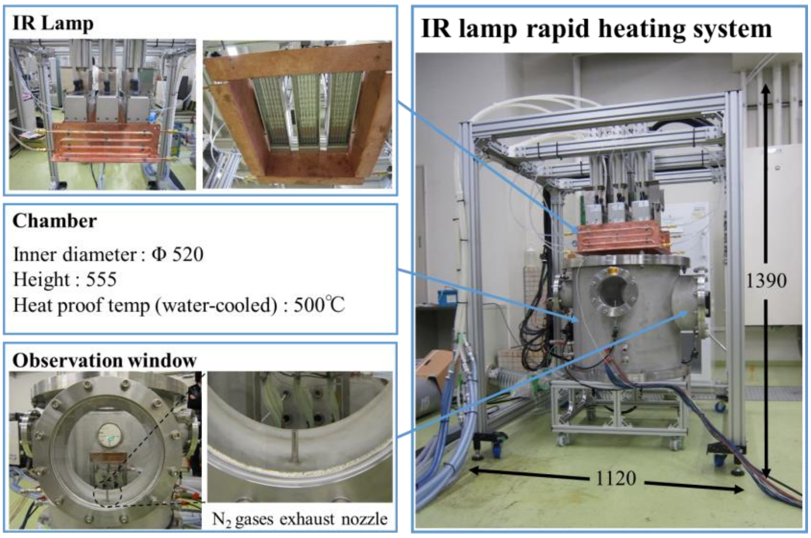

Figure 1. IR Lamp Rapid Heating System.

2.2. Digital image correlation method

Furthermore, thermal deformation values of CFRP is obtained by Digital Image Correlation Method which is an optical, non-contact method to measure full-field displacement and strains. And by using stereo vision technique and DIC method, we can measure shape, displacement and strain of the three-dimensional objects. Figure 2 (a) shows the concept of DIC, (b) shows the concept of streo vision technique and (c) shows the situation of taking a photograph with two cameras [3]. Several studies have reported that digital image is affected by radiation under high temperature environment [4]. For this reason, we install optical filters in two cameras which can shut out the long wavelength light. And, the random pattern made by common paints normally burns out at temperatures above 250°C. Therefore, in this work, we used the ceramic adhesive for random patterns.

2.3. Condition of rapid heating test

The heating time is 60sec and heat flux is 76kW/m^2. And the specimen is a CFRP laminates. This CFRP is non-woven fabric. Figure 3 is the photo during rapid heating test.

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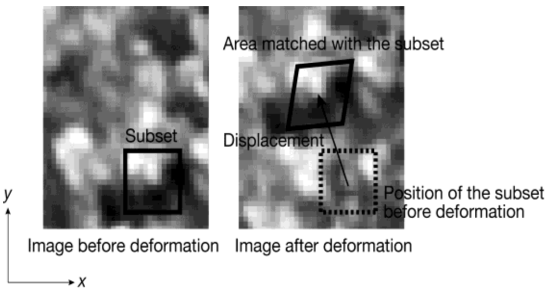
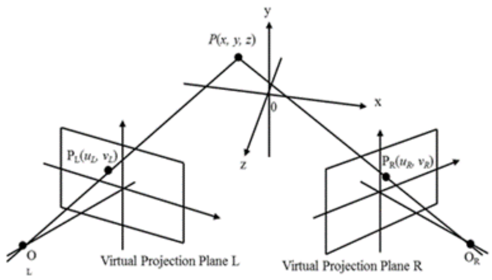
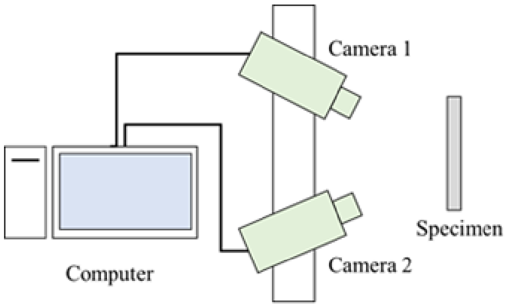


(a) Concept of DIC



(b) Concept of stereo vision technique



(c) Set up for Stereo DIC

Figure 2. Stereo DIC technique.

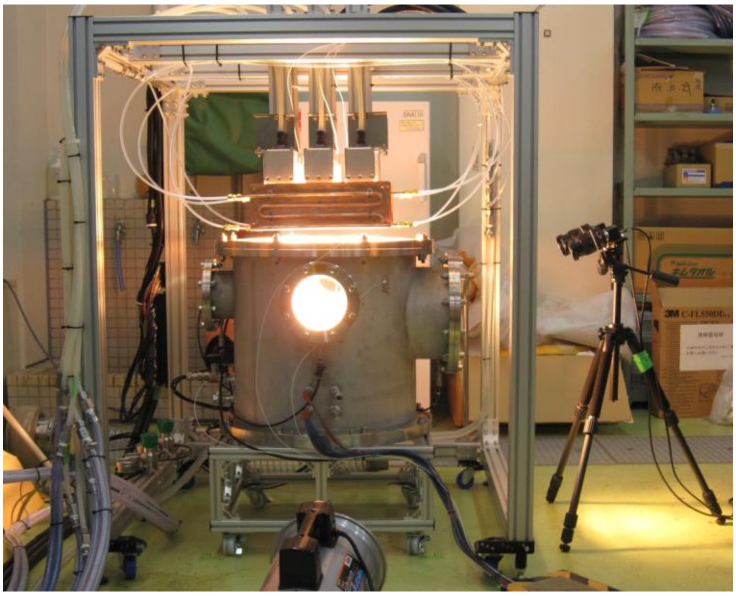


Figure 3. Photo during rapid heating test.

3. Test results and discussion

Figure 4 shows the history of out-of-plane displacement distribution. In an early stage, the CFRP laminates warped by temperature difference in thickness direction. But, after that, specimen deformed locally.

The mechanism of out-of-plane deformation with local damage is assumed as follows. Phenol resin causes pyrolysis at 300°C and generates pyrolysis gas such as CH_4, OH^- and C_6H_6. The mass flux, permeability, and pressure of the pyrolysis gas are related by Darcy's law. This delamination behavior does not occur under quasi-static heating, because the pyrolysis gas is able to permeate toward the side and be discharged. Meanwhile, in the rapid heating, the pyrolysis gas generation rate is higher than

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the diffusion rate. Consequently, increase internal pressure causes internal damage. This internal damage makes thermal deformation of CFRP under rapid heating irrecoverable. Figure 5 shows that mechanism.

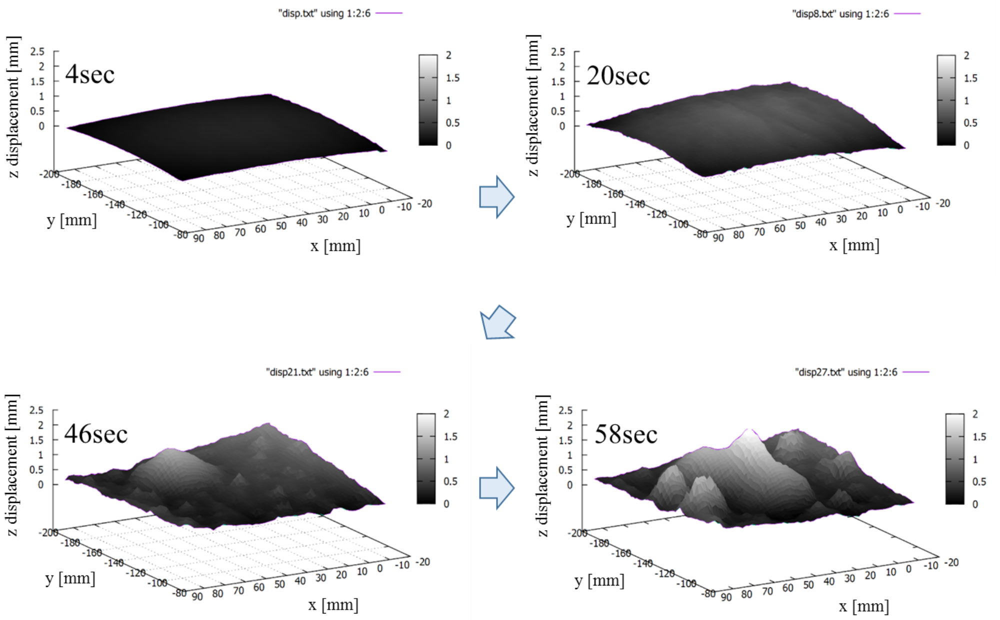

Figure 4. z-direction displacement change with heating time

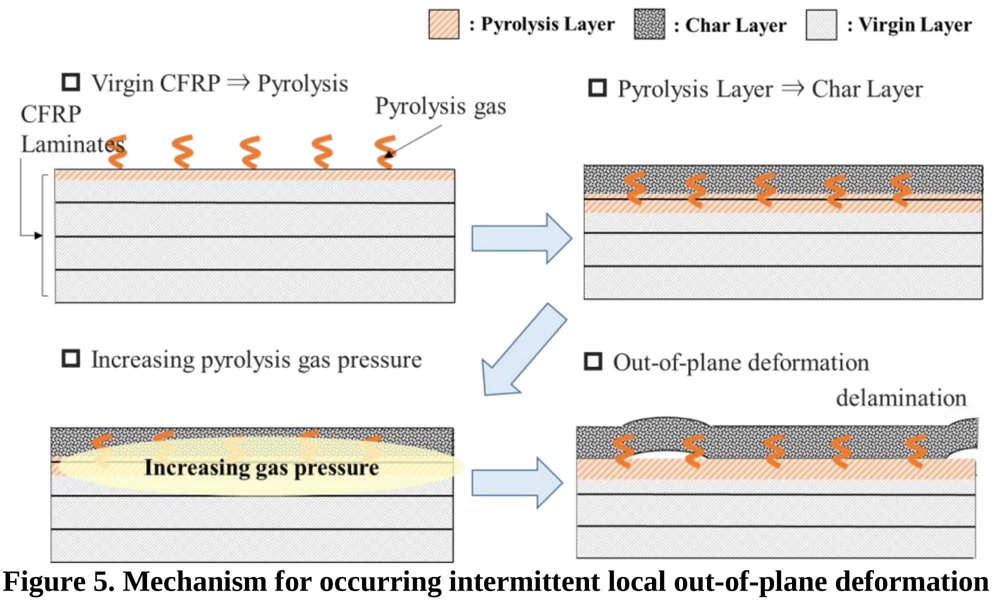

Figure 5. Mechanism for occurring intermittent local out-of-plane deformation

4. Analytical procedure

In this section, we did multi physics simulation involving thermal transfer, carbonization, pyrolysis reaction, gas generation, internal pressure enhancement so as to investigate the phenomenon as mentioned before. The flow chart of solving process is shown in Figure 7. In this study, we solved the present problem by using finite difference form. In order to convert the continuous problem into discontinuous problem in space domain, the specimen is meshed in the through-thickness direction; it is shown in Figure 8.

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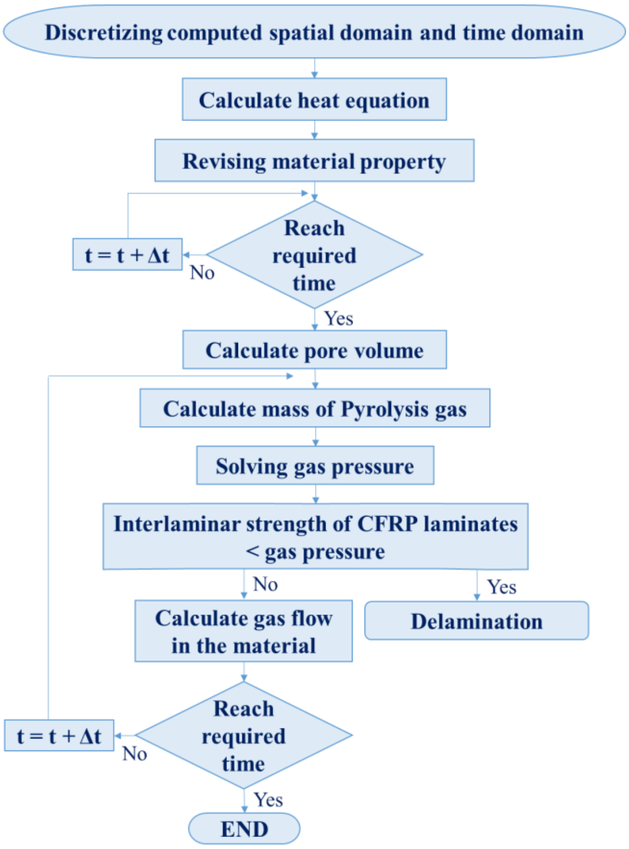

Figure 7. Flow chart of solving process

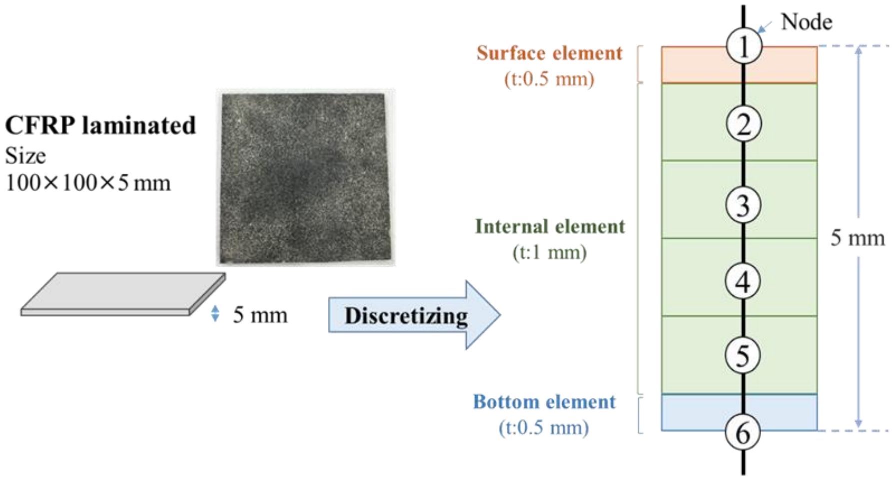

Figure 8. Model of specimen for CFRP in the thickness direction

For the first step, we solved heat equation and determined temperature distribution of the ablator. The heat equation is given by the following expression

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) \qquad (1)$$

At that time, we consider irrecoverable non-linear variations of material property such as density, thermal conductivity and specific heat. Note that, conduction and heat loss quantity during pyrolysis are not taken into account. Next, we calculate the volume of pore which generates within the specimen. Then, it is assumed that volume of pore is calculated by transition of density during heating. And then, we calculate mass of gas that is existing in pore. The mass conservation equation is consisted of three terms, “Generating gas”, “Outflow of gas” and “Inflow of gas”. The mass of

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generated gas is calculated by density with low of conservation of mass. In this study, we assumed that the gas flow is governed by Darcy's law:

$$\dot{m} = -D\frac{\partial P}{\partial x} \tag{2}$$

This equation represents that the gas flow speed rely on the gradient of internal pressure. And the gas pressure in pore is calculated using the equation of state in the following form:

$$PV=nRT \tag{3}$$

As explained above, the mass of pyrolysis gas generated into the material is calculated by these procedures. Moreover, the history of the pore pressure is calculated simultaneously. By comparing the pore pressure with the interlaminar strength of CFRP laminates, we will verify whether above mechanism is able to cause the delamination or not.

Conclusion and Future Works

In this study, experimental devices are developed and discussed; these devices can rapidly heat to measure local and irrecoverable deformation of CFRP by Stereo DIC method. By using optical filter and ceramic adhesive, we can measure displacement at high temperature with Stereo DIC method. From the results, we can measure the local out-of-plane deformation with internal damage due to increasing pressure of the pyrolysis transitionally. We propose the analytical procedure which investigate the mechanism of the out-of-plane deformation with local damage of CFRP under rapid heating.

In the future, by comparing the pore pressure with the interlaminar strength of CFRP laminates, we will verify whether above mechanism is able to cause the delamination or not. And some studies have demonstrated that the cohesive element model is able to represent the interface fracture model [5, 6]. Therefore we will use that model and investigate the behavior of CFRP under rapid heating.

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References

[1] J. Koyanagi, K. Hirai, A. Nakazato, R. Inoue, T. Ube, Estimation of the Highest Surface Temperature for CFRP Ablator by Raman Analysis, *Transaction of Japan Society for Aeronautical and Space Sciences*, (Under review)

[2] J. Koyanagi, Y. Fukuda, S. Yoneyama, K. Hirai, A. Yoshimura, T. Aoki, T. Ogasawara, Local out-of-plane deformation of CFRP ablator under rapid heating, *Advanced Composite Materials*, (Under review)

[3] S. Yoneyama, Computing strain distributions from measured displacements on a three-dimensional surface, *Journal of Japanese Society for Experimental Mechanics*, 10:113-118,2010

[4] B.Pan, D. Wu, Z. Wang, Y. Xia, High-temperature digital image correlation method for full-field deformation measurement at 1200°C, *Measurement science and technology*, 22:1-11,2011

[5] J. Koyanagi, A. Yoshimura, H. Kawada, Y. Aoki, A numerical simulation of time-dependent interface failure under shear and compressive loads in single-fiber composite, *Applied Composite Materials*, 17:31-41,2010

[6] J. Koyanagi, Y. Sato, T. Sasayama, T. Okabe, S. Yoneyama, Numerical simulation of strain-rate dependent transition of transverse tensile failure mode in fiber-reinforced composites, *Composites Part A*, 56:136-142,2014

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