IN-SITU STRAIN MONITORING IN PREPREG PLACEMENT PROCESS USING DISTRIBUTED OPTICAL FIBER SENSOR

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ABSTRACT

Automatic prepreg layup system has been developed to achieve consistent quality and high productivity of advanced composites. It opens up new markets and applications for composite products in aerospace and automotive. Automated Fiber Placement (AFP) is a process that uses computer-controlled robotic arm to lay bands of prepreg strips onto a mould in order to create a part or structure. Prepreg strips are pulled tightly to prevent the occurrence of a wrinkle and a kink and, as a result, initial tensile stress is induced in the laid up prepreg strips, which can affect the residual stress and shape distortion. In addition, it is expected that the initial stress gradually relaxes after the layup. However, this stress development and relaxation have not been clarified yet. Therefore, it is necessary to establish a reliable monitoring method. In this study, an optical fiber sensor was used to monitor strain change during layup of prepregs. First, a preliminary test was conducted. An optical fiber was placed on the surface of a prepreg strip along the longitudinal direction. Then, the prepreg with the sensor was preheated to 70°C and cooled down to room temperature rapidly in order to unify the optical fiber sensor and the prepreg and to enhance the strain transfer between them (hereinafter, this prepreg with an optical fiber sensor is called "sensing prepreg"). This prepreg was pulled with a tensile testing machine and the strain was measured with the optical fiber sensor. The strain measured with the optical fiber sensor agreed well with the strain estimated from the load applied to the sensing prepreg, confirming that embedded optical fiber sensors can measure strain of prepreg strips. In addition, the sensing prepreg was utilized to investigate stress development and relaxation in a simulated AFP process.

1 INTRODUCTION

Automatic prepreg layup system has been developed to achieve consistent quality and high productivity of advanced composites [1, 2]. It opens up new markets and applications for composite products in aerospace and automotive. Automated Fiber Placement (AFP) is a process that uses computer-controlled robotic arm to lay bands of prepreg strips onto a mould in order to create a part or structure. Fig. 1 shows a schematic of an AFP head. Prepreg strips are pulled tightly to prevent the occurrence of a wrinkle and a kink and, as a result, initial tensile stress is induced in the laid up prepreg strips, which can affect the residual stress and shape distortion. In addition, it is expected that the initial stress gradually relaxes after the layup. However, this stress development and relaxation have not been clarified yet. Therefore, it is necessary to establish a reliable monitoring method.

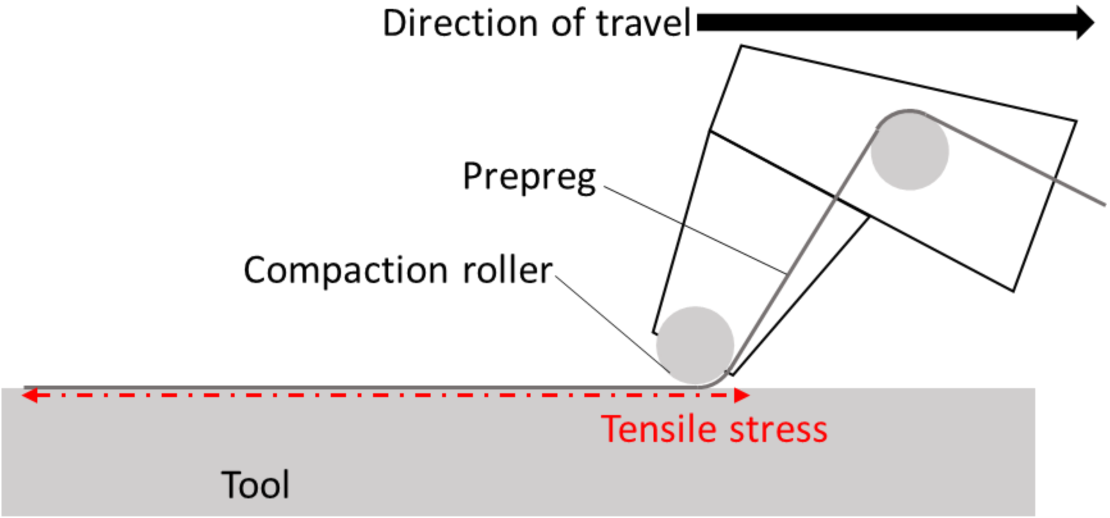

Fig. 1 Schematic of an AFP head

This current study develops a fiber-optic-based approach. An optical fiber sensor is unified to a prepreg strip and strain change during its placement process is monitored using a distributed strain sensing system. First, tensile tests are conducted using prepreg with optical fiber in order to confirm that the strain distribution of prepreg can be measured with an optical fiber sensor. Next, the tensile loading-unloading simulating AFP process is applied to the prepreg and the strain change during layup is monitored.

2 TENSILE TEST FOR PREPREG STRIP WITH AN OPTICAL FIBER SENSOR

A tensile test was conducted to validate the proposed approach using an optical fiber sensor by measuring stress development and relaxation in prepreg strips.

2.1 Specimen and test method

The optical fiber sensor (cladding diameter 125 μm, polyimide-coating diameter 150 μm) was embedded in the center of the specimen by 500 mm along the longitudinal direction which was the carbon fiber direction in the prepreg (T700SC/2592, Toray Industries, Inc., 600 mm × 20 mm, 1ply). Teflon film (thickness 0.05 mm) was placed on the top and bottom of the specimen for demolding and a breather was placed on the specimen as a flow path of air. Then, the prepreg with the optical fiber sensor was heated from room temperature to 80℃, which was the softening temperature of the prepreg, in order to unify the optical fiber sensor and the prepreg and immediately cooled down to room temperature. By this process, stress transfer between the optical fiber and the prepreg was improved (hereinafter, this prepreg with an optical fiber sensor is called “sensing prepreg”). Full vacuum was applied before heating the specimen. Cure reaction did not proceed significantly in the heating process due to low temperature and short holding time. Figure 2 presents a cross-sectional X-ray CT scan image of the sensing prepreg. It is clear that the optical fiber sensor and the prepreg were unified.

Figure 3 depicts the schematic of the specimen used in the tensile test. Tabs made of sandpapers (40 mm × 30 mm) were bonded to both sides of the sensing prepreg. This sandpaper tab prevented slippage between the head of the tensile testing machine and the sensing prepreg. This prepreg was pulled with a tensile testing machine and the strain along the optical fiber was measured using distributed sensing system (ODiSI, Luna). The tensile

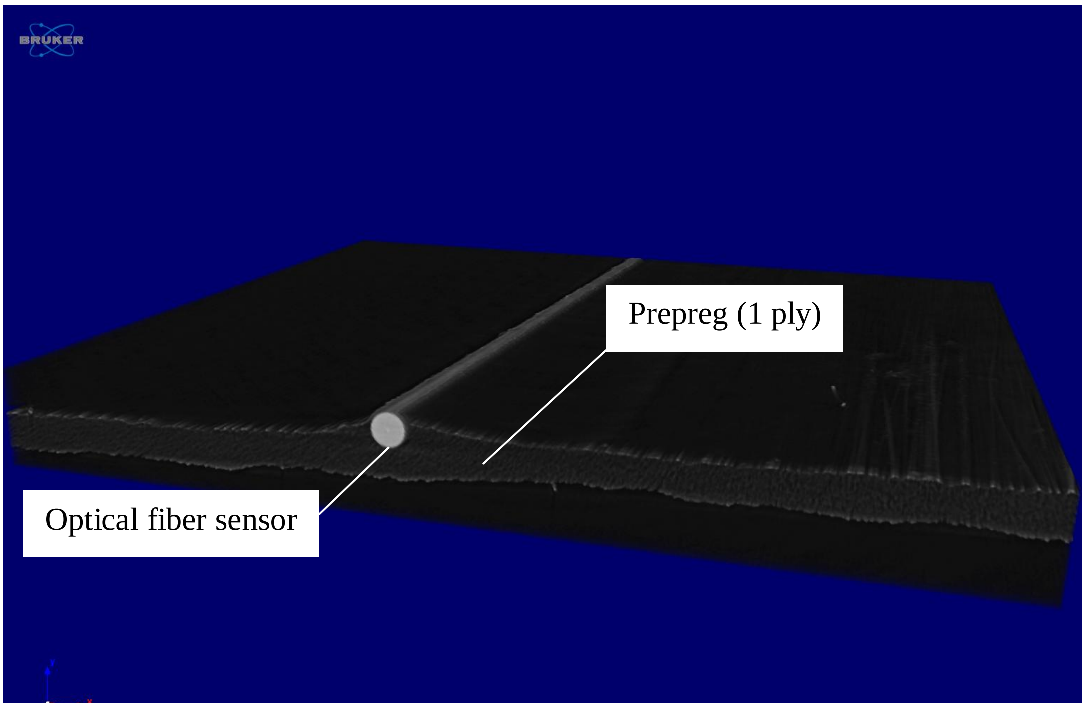

Fig. 2 Cross-sectional X-ray CT scan image of sensing prepreg

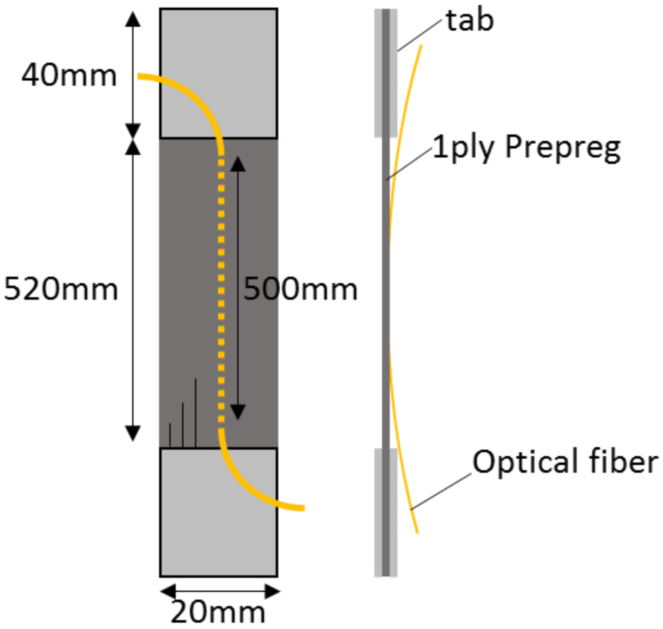

Fig. 3 Schematic of tensile test specimen

test was carried out three times consecutively using the same specimen. In the tensile test, after reaching an arbitrary load at displacement control of 0.1 mm/min, load was held for 3 minutes and unloading was carried out.

2.2 Results and discussions

Figure 4 presents the result of strain distribution in the loading test. It can be seen that the strain distribution is not uniform from the center to the end of the specimen, and the approximate shape is trapezoidal. This is due to the shear-lag effect at the end of the embedded part. That is, strain is not sufficiently transferred from the base material to the optical fiber sensor at the end of the embedded optical fiber sensor. The degree of shear-lag occurring at the end of the optical fiber sensor depends mainly on the shear modulus of the matrix that unite the prepreg and the optical fiber. The larger the shear modulus of the matrix is, the smaller the degree of shear-lag. The strain is relaxed from -110 mm to -80 mm and from 90 mm to 130 mm during tension holding (from 7.0 min to 10 min). It is considered that stress relaxation caused the slippage of the optical fiber sensor the interface between the optical fiber and the prepreg during tension holding. In contrast, it is clear that the optical fiber sensor did not slip at the central part of the specimen from -80 mm to 90 mm. From this, it is suggested that for the sensing prepreg with the optical fiber sensor 500 mm long, the strain at the central part of the prepreg of 170 mm (corresponding to the length of 34% with respect to the embedded length) can be sufficiently measured with the optical fiber sensor.

Furthermore, the strain history and load-strain curve at the center of the specimen (0 mm in strain distribution Fig. 4) are shown in Figs. 5 and Fig. 6. In the strain history (Fig. 5), benchmark strain value is added from the calculation using the load value and Young’s modulus of the prepreg (E = 130 GPa). The strain history in Cycle 1 (Fig. 5) shows a good agreement with the theoretical value. After Cycle 1, however, the strain transfer from the prepreg and the optical fiber was not sufficient. This is because the interface between the optical fiber sensor and the prepreg became weak during the first tensile loading and unloading, and the optical fiber sensor slipped. In the load-strain curve (Fig. 6), the result of Cycle 1 shows that the strain is linearly related to the load both during loading and unloading. However, in Cycle 2 and Cycle 3, the linearity is lost. In summary, it was confirmed that the strain occurring in the prepreg strip can be measured by the embedded optical fiber sensor in a single loading cycle. It is important to note that loading and unloading are not repeated in actual AFP processes. Therefore, it can be said that strain measurement with a sensing prepreg is possible.

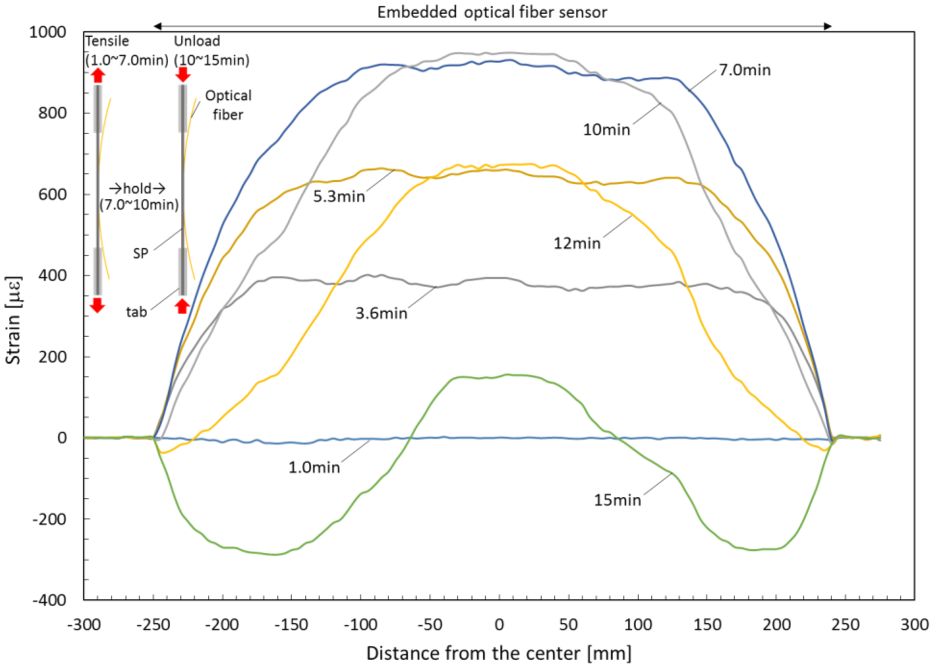

Fig. 4 Tensile strain distribution profile of sensing prepreg along the distributed optical fiber sensor

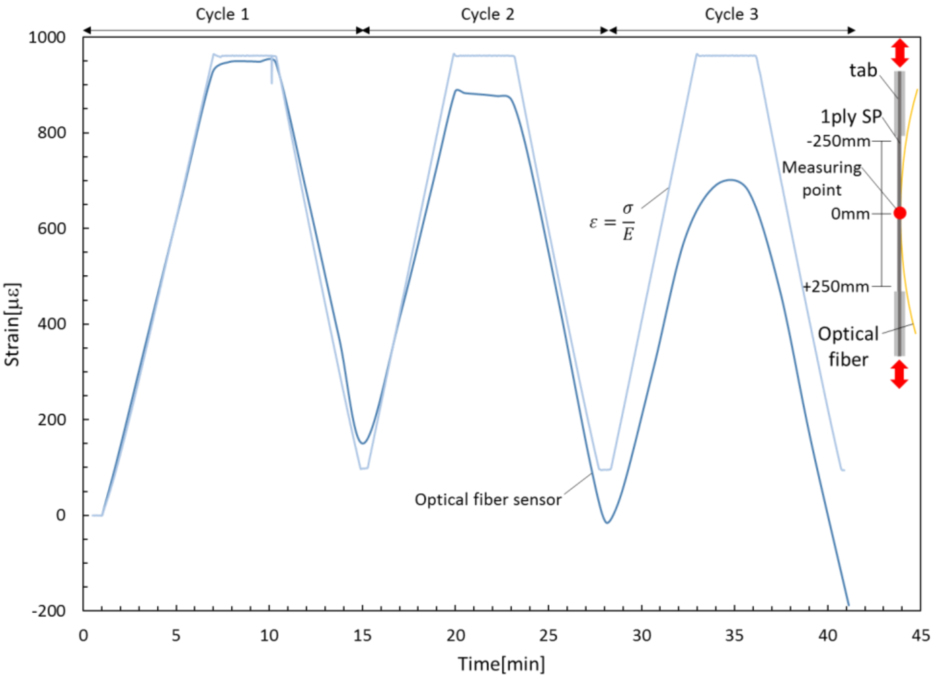

Fig. 5 Strain profile of the center at sensing prepreg obtained by the distributed optical fiber sensor

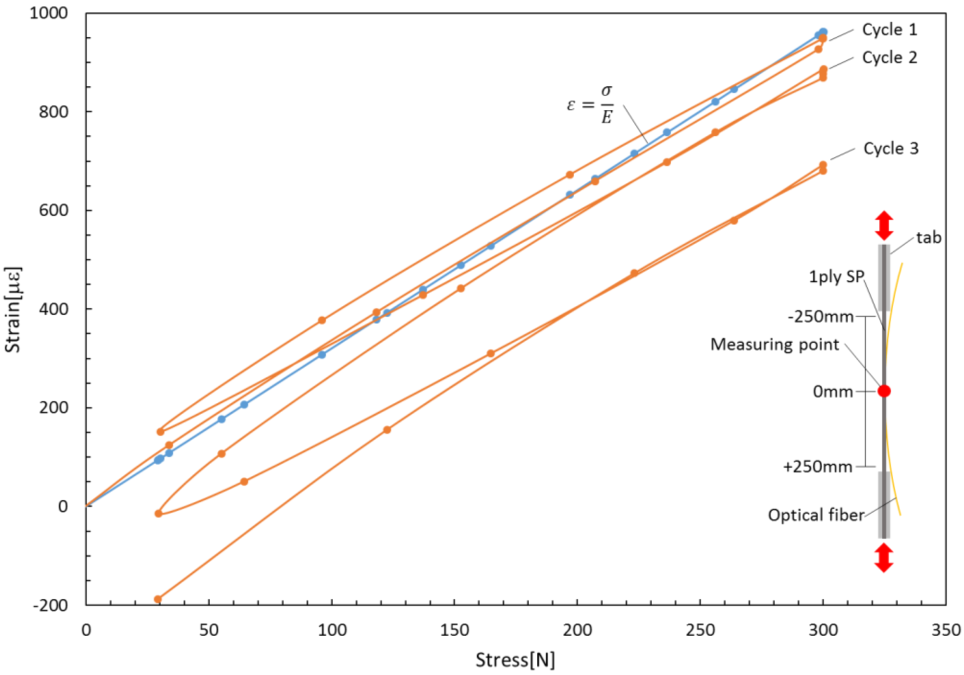

Fig. 6 Strain-load curves obtained by the distributed optical fiber sensor

3 THE EFFECT OF TOOL-PART

Tensile test simulating tool-part interaction was conducted. After tensile loading was applied, an aluminum tool was pressed to the sensing prepreg to simulate prepreg placement process by AFP.

3.1 Specimen and test method

As in Section 2, two pairs of specimens with sandpaper tabs were produced. The shape of the specimen (1 ply prepreg) was 600 mm × 20 mm, and an optical fiber sensors was embedded by 500 mm. Outline of the test compared with the AFP process is summarized in Fig. 7. In process A, the sensing prepreg was pulled with a tensile testing machine. This is a process simulating the tension of prepreg strip by AFP head. In the tensile test, after reaching an arbitrary load at displacement control of 0.1 mm/min, the sensing prepreg was pseudo-laminated on the aluminum tool at the time of holding the load, and this was taken as Process B. This is a process simulating the state of prepreg strips stacked by AFP's head and placed on tool. Thereafter, unloading was carried out as process C. This is a process simulating cutting and subsequent stress relaxation that can occur in the prepreg until curing. The strain was measured with the optical fiber sensor from process A to C.

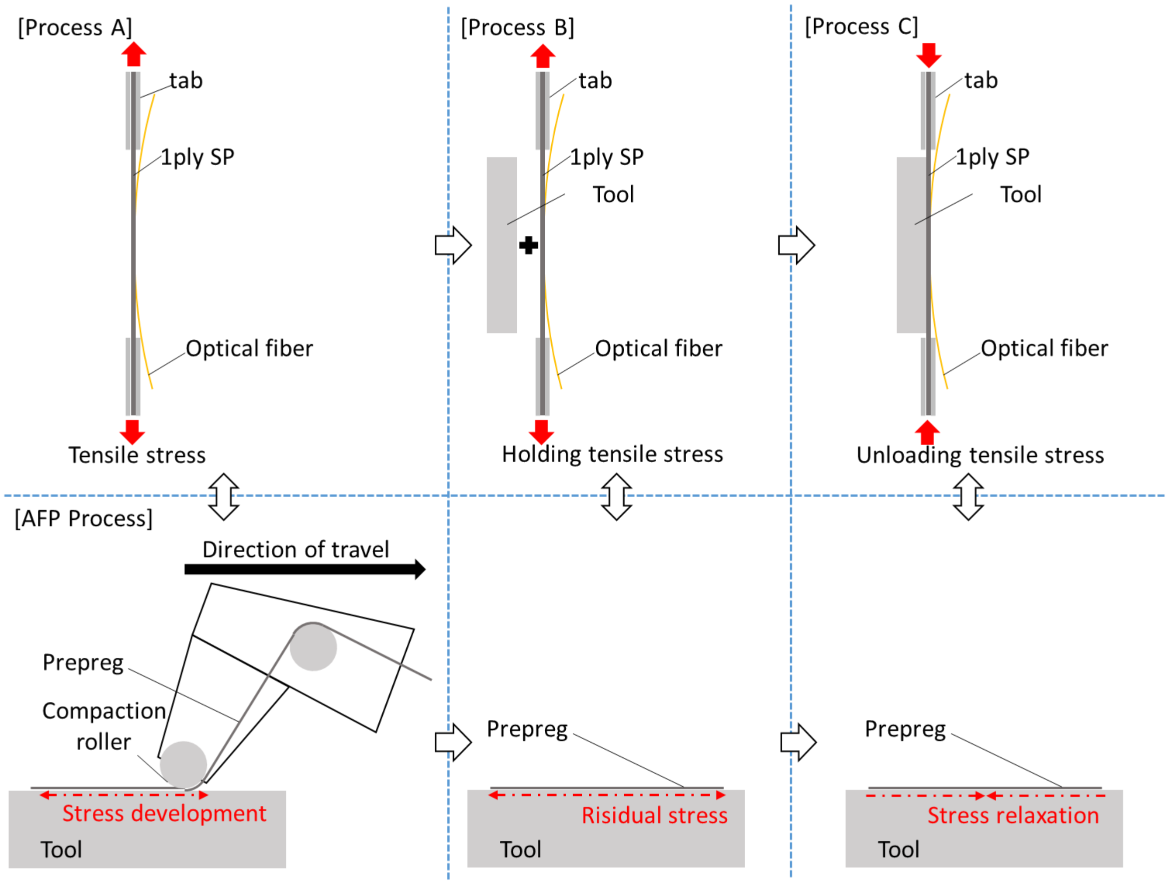

Fig. 7 Outline of the test compared with the AFP process

3.2 Results and discussions

A load-strain curves during unloading at -100 mm from the central part of the specimen is shown in Fig. 8. When unloading from 300 N to 60 N, the tensile strain was not fully unloaded in the case with tool. This indicates that the deformation of the prepreg was partially locked by tool-part interaction and the tensile strain remained. Furthermore, the residual tensile strain gradually relaxed during at the time of unloading from 60 N to 50 N. This suggests that the shearing force between the tool and the prepreg relaxed and the tensile deformation locked by the tool-part interaction was released. The result above successfully confirmed the feasibility of the proposed fiber-optic approach to monitor stress development and relaxation during AFP processes.

4 CONCLUSIONS

In this paper, we first fabricated a sensing prepreg by placing an optical fiber on the surface of a prepreg and preheating it to unify the optical fiber sensor and the prepreg. By applying tensile loading to this sensing prepreg, we validated the measurement of strain development in prepreg with the optical fiber sensor. We successfully measured the distribution of layup-induced tensile strain, which has significant impact on products made by AFP processes. Furthermore, it was suggested that the tensile strain generated at the lamination is relaxed. Future works will investigate the dependence of the strain relaxation on specimen geometry. Optical fiber sensor can continuously monitor strain during layup, curing and operation. So, future work will also address the change of the layup-induced stress/strain in the following process steps.

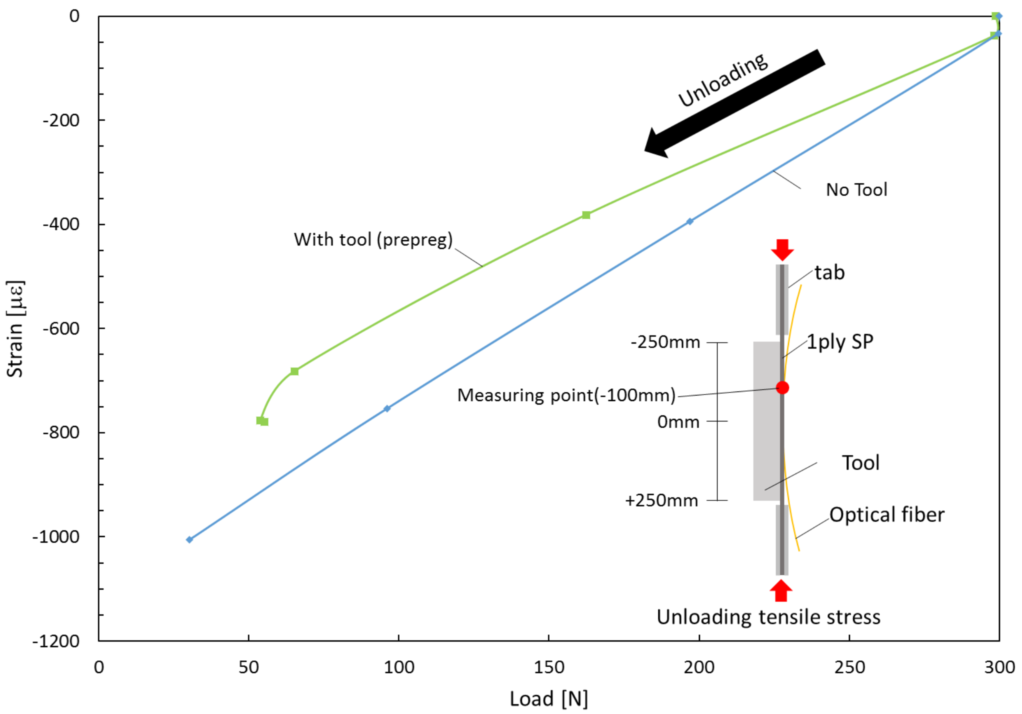

Fig. 8 Strain-load curves obtained by the distributed optical fiber sensor at -100 mm from the center.

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