1 Introduction
A long-term durability of composite materials is of importance as the material application fields are spreading. In order to obtain the most fundamental information of the long-term durability, simple mechanical tests using straight specimens have been carried out [1-3]. The SFF theory [1] presented by Koyanagi et al enables us to predict time- and temperature-dependent composite strengths in fiber longitudinal direction. The SFF theory needs to know only three strengths of reinforcing fiber, matrix and interface to estimate the composite strength; if time and temperature dependence of them are known, those of composites can be estimated easily. However, when more complex tests are performed, containing cracks and/or notches, the analysis should be more difficult because of the strain gradients around the damage. Time-dependent failure and progress of the damage for the notched composites have not been studied enough.

There have been articles dedicating the static strength of notched composite laminates [4-11]. One of the important keys to investigate the strength of the notched composites is observation of the strain gradient considering internal damage which is invisible at the specimen surface. A full-field strain measurement employing digital image correlation (DIC) technique has been done to investigate strain gradient affected by internal damage [4, 5]. This method allows predicting the internal damage progress and ultimate failure behaviors much more precisely than conventional combination of strain gauge and damage detection such as CT scan using interrupted test specimen. Recently, successful failure simulations of the notched specimen have been reported in several articles, considering threedimensional size-scaling, i.e. size of hole diameter and/or depth and stacking sequence of laminates [9-11], but still limited at static condition.

The present paper aims to investigate long-term reliability of the open-hole composite laminates under a constant load at various test temperatures. Employing the DIC method, time-dependent occurrence or progression of internal damage around the hole is in-situ observed and the effect of them on ultimate failure strength is discussed. For accelerated testing, test temperature is elevated. The constant load test is interrupted by one hour and the residual strength is examined. A relationship between constant load duration time which is estimated using time-temperature superposition principle and residual strength of the interrupted specimen is investigated.

2 Experimental
In the present study, a rectangular specimen with a center hole is employed. The stacking sequence of this laminate is [90°/45°/-45°/0°]s, a quasi-isotropic laminate consisting of total 8 ply. Reinforcing fiber is T300 (Toray), and matrix is a general epoxy resin. The laminate was fabricated by an autoclave at 120 °C for 2 hours. Figure 1 shows specimen dimensions and geometry and magnified photograph around the center hole. Both surfaces of both specimen ends, GFRP tabs are attached. For the DIC measurement, black and white patterning is made on the specimen surface shown in Fig. 1. Figure 2 shows the experimental set-up employed in the present study. The set-up consists of a general tensile testing machine, a heating system, and DIC system. This study investigates time-dependent change of the full-field strain distribution under a constant load; many photographs are taken historically. For the DIC, the
center hole is better to be fixed on each photograph. Generally, the constant load generates creep strain. If one crosshead of the testing machine is controlled and another is fix, the hole position will move with the creep strain. In order to avoid this issue, the original chucking equipment is used as shown in Fig. 2. By this chucking system, the hole position is kept at the same position independently of the specimen creep strain. Note that specimen load is half of testing load using this chucking method. The specimen including chucking system is heated by a thermostat bath. Images are taken outside of the thermostat bath.

The constant specimen load is 1250N which is 70% of static specimen failure load for this specimen. The duration time subjected to constant load is 1 hour. The test temperature is varied from room temperature 20 °C to 110 °C with each 30°C interval. Based on time-temperature superposition principle, test time is accelerated by elevated temperature for the polymeric materials. The accelerated shift log time is given by

\[
\log_\alpha(T_{test}) = \frac{\Delta H}{2.303 \cdot G} \left( \frac{1}{T_{ref}} - \frac{1}{T_{test}} \right) \quad (1)
\]

where G is the gas constant 8.314x10^-3 kJ/(K mol), T_{test} is the test temperature (K), T_{ref} is the reference temperature (K) and \(\Delta H\) is the activation energy. The reference temperature in this case was 293 K (20°C). The activation energy 150 [kJ/mol] presented by a ref. (3), in which the identical material is used, is assumed. According to this assumption, 110°C 20 hours corresponds to 135°C 1hour. For the reference, each test condition corresponds to each test time shown in following table when assuming room temperature. Hereafter, 110°C 20 hours is referred as 135°C for convenience in the present study.

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Correspondence time at 20°C [hour]</th>
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<tbody>
<tr>
<td>20°C 1 hour</td>
<td>1</td>
</tr>
<tr>
<td>50°C 1 hour</td>
<td>309</td>
</tr>
<tr>
<td>80°C 1 hour</td>
<td>3.6x10^4</td>
</tr>
<tr>
<td>110°C 1 hour</td>
<td>2.0x10^6</td>
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</tbody>
</table>

3 Result and discussion

Figure 3 shows example of displacement distribution regarding load direction. From the displacement distribution, strain distribution can be obtained by partial differentiation.
The constant test load is 2500N. The test temperatures are 20, 50, 80, 110°C. Fig. 4 shows typical experimental results of full-field strain distribution measurement by the DIC method. For the results, relatively low temperature condition makes less significant difference between before and after 1 hour constant load duration. That implies fatal internal damage does not occur. On the other hand, for the relative high temperature conditions, strain around the notch increase significantly compared with before testing. That means internal damage occurs or progress during the tests.

Figure 5 shows residual strength measurement results. For the results, there is no significant difference when the test temperatures are different. For the meantime, this result implies that even though the internal damage progresses with constant load, the residual strength does not change significantly. However, the number of the test specimen might be not enough; we are still investigating this now. In near future, we will quantify the internal damage progress and residual strength using damage mechanics.
4 Conclusion
This study measured full-field strain of notch composite laminates during constant load under various temperature conditions, and the residual strengths. Although the temperature difference makes very different DIC results, the residual strengths are not different significantly. This implies notched specimen strength is insensitive with internal time-dependent progressive damage in the range of this study.

References