RELATIONSHIPS BETWEEN DEGREE OF SKILL, DIMENSION STABILITY AND MECHANICAL PROPERTIES OF COMPOSITE STRUCTURE IN HAND LAY-UP METHOD


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1 Introduction

Hand lay-up (HLU) method is used as one of the forming techniques of a fiber-reinforced plastic (FRP) for many years. This is because HLU method only requires raw material, mold and human skill, also it can respond to change of quantity of the product or a size widely. Therefore the skill of those who fabricate influences the quality of a product greatly. For this reason, such as FRP fabrication proficiency measurement are used and instruction to a beginner is advancing. However, it is not clarified until now about a craftsman's skill which is called "TAKUMI" of hand lay-up skill. Moreover, it is not clarified about the relation between a craftsman's level of skill and quality of the product, which means mechanical properties and dimensional stability, etc.

On the other hand, if a reinforcement base material, a reinforcement form, base material resin, and volume content are the same, no matter what forming method it may use, it is thought that the characteristic of the composite becomes the same. The essence of FRP fabrication is replacing the air which makes resin impregnate with a fiber and which in other words is contained in the fiber by resin. Resin is made to impregnate with a strengthening fiber by using a roller in HLU method. Therefore, it is suggested that the methods of impregnation has the possibilities to produce change of interfacial quality. In this study, in order to consider the influence of the roller in the HLU method to the mechanical property of a composite material, the FRP specimen was produced by the craftsman (an expert and an unskilled operator) who has a work experience of bathtub manufacture by the HLU method. The strength test of a specimen and observation of dimensional stability which were obtained by the process analysis were performed, and the analysis of a craftsman's level of skill and the relation of mechanical properties were taken place.

2 Experimental procedure

2.1 Subject

In this study, two persons, an expert HLU engineer (right-handed male, 48 years old, 25 years of work carrier) and a non-expert (right-handed male, 29 years old, 1 year of work carrier), were targeted. Biological data of subjects is shown in Table 1.

Table 1 Biological data of subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Career (year)</th>
<th>Height (cm)</th>
<th>Weight (Kg)</th>
<th>Dominant-Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert</td>
<td>48</td>
<td>25</td>
<td>171</td>
<td>52</td>
<td>Right</td>
</tr>
<tr>
<td>Non-expert</td>
<td>29</td>
<td>1</td>
<td>164</td>
<td>56</td>
<td>Right</td>
</tr>
</tbody>
</table>
2.2 Analysis object

Analysis object was work which fabricated a composite by HLU method. The size of the mold was as follows. 415 mm in length, 1600 mm in width, and 50 mm in height. The mold used by this study is shown in Fig.1.

![Fig.1 Mold used in this study.](image1)

2.3 Materials

In the mold surface, 0.5mm gel-coat (white-color) is sprayed in advance. After that, lamination by the HLU method was started.

Glass chopped fiber mat was used as reinforcement with a density of 380 g/m² which was made of glass fiber in the length of 50 mm. And isophthalic type unsaturated polyester resin was used as matrix. Polymer was mixed with the hardener MEKPO in a ratio of 100:1.0.

2.4 Three-dimensional motion measurement

Motion analysis and eye movement measuring was done from start to finish of all the work process for clarifying the degree of skill.

Three-dimensional motion measurement was performed using MAC3D System (manufactured by Motion Analysis Corporation), that is an optical real-time motion capturing system (Fig.2). Before measurement, in order to acquire the three-dimensional coordinates of makers, L shaped frame (which the infrared markers attached) was shot and the calibration of the shooting range was performed using T shaped wand (which two infrared markers attached). A total of 24 infrared reflective markers were attached to subject’s body (Fig.3). Similarly, 3 markers were attached to the tools (Fig.4).

The position of each marker was captured with 5 cameras (manufactured by Motion Analysis Corporation), and the three-dimensional position data of all the markers was synchronously downloaded to the PC (sampling rate : 60Hz). Moreover, the data of one digital video camera also synchronized simultaneously. In addition, horizontal direction toward the working table was defined as the X-axis, vertical direction as Y-axis, and height direction as Z-axis.

As data processing, the coordinate data of a total of 24 markers attached to each joint was obtained using EvaRT Ver5.0.4 software (manufactured by Motion Analysis Corporation).

![Fig.2 Motion analysis system in this experiment](image2)

![Fig.3 24 markers were attached to subject’s body (infrared reflective marker which is being reflected white)](image3)

![Fig.4 three markers were attached to tools (woolen-roller, finishing-roller)](image4)
2.5 Eye movement measurement

The eye movement measurement was performed using Talk Eye II (manufactured by Takei Scientific Instruments.co.,ltd.) for analyzing eye movement. Goggles-like apparatus was attached to subjects. Subject’s view was captured with the camera which was existed at the center of both eyes, and two cameras of both sides detected a look-at-point. The sampling rate was 30 Hz. Moreover, two digital video cameras were used to record motion of objects. Cameras were arranged so that motion could be captured clearly. Eye movement measurement system is shown in Fig.5. And experiment scene is shown in Fig.6.

![Eye movement measurement system](image1)

Fig.5 Eye movement measurement system

2.6 Mechanical property

The composite structures were cut for the tensile testing (Fig.7). After cutting the specimens, 10mm hole were drilled in the geometric center of the specimens. specimen size is 150mm*30mm (Fig.8). A circle hole part is easy to be destroyed in order that stress may concentrate. Therefore, it differs from the data obtained from a specimen without a circle hole.

However, in Automotive and Aerospace field, when real use of FRP structure is supposed, hole drilling for attachment of component etc. is indispensable. So, in this study, the specimen with a circle hole was also used for a valuation method according to real use. Tensile test were performed by using an Instron universal testing machine under a speed 1mm/min.

![Specimens for tensile testing](image2)

Fig.6 Experiment scene in this study

Fig.7 Sampling of specimens for tensile testing.

2.7 Dimension stability

The dimensional stability of Expert and Non-expert was compared from the surface and cross-sectional observation of FRP products which were fabricated in this study. The plane area of composite structures were cut (Fig.9), and the roughness of plane were measured by micrometer.
Furthermore, the composite were cut off for sectional view (Fig.10).

Fig.9 Sampling of specimens for roughness of plane.

Fig.10 Sampling of specimens for sectional view.

4 Results and consideration

4.1 Process analysis

Process analysis was performed in detail based on the data shot with digital video cameras. First, the working process could be subdivided. And the working hours of each subdivided phase were recorded. Results of process analysis are shown in table 2.

The process could be subdivided into three process (fabrication process 1, fabrication process 2, and finisher process).

“Fabrication process 1” was defined as the fabrication using glass roving. “Fabrication process 2” was defined as fabrication using glass chopped strand mat. And then “Finisher process” was defined as surface finishing.

Furthermore, fabrication process1 could be subdivided into two phases, fabrication process 2 could be subdivided into seven phases, and finisher process could be subdivided into two phases (see the table 2).

At all the phases except phase 9, Non-expert’s working-hours were longer than Expert’s.

### Table2 Schema of working process

<table>
<thead>
<tr>
<th>Process</th>
<th>phase</th>
<th>Working-time [sec.]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Expert</td>
</tr>
<tr>
<td>Fabrication process1</td>
<td>1. Impregnating glass-roving with resin</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>2. Arranging impregnated glass-roving to corner part</td>
<td>53.1</td>
</tr>
<tr>
<td></td>
<td>3. glass-mat (small-size) were placed in the center of mold</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>4. Impregnating glass-mat with resin. And undercoating shorter sides</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td>5. Arranging impregnated glass-mat to shorter sides</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>6. Undercoating the whole mold</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>7. glass-mat (large-size) were placed in mold</td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td>8. Impregnating glass-mat with resin.</td>
<td>172.8</td>
</tr>
<tr>
<td></td>
<td>9. Smoothing the surface with woolen-roller</td>
<td>32.1</td>
</tr>
<tr>
<td>Finisher process</td>
<td>10. Finishing plane part with finishing-roller</td>
<td>68.0</td>
</tr>
<tr>
<td></td>
<td>11. Finishing corner-parts and standup-parts with finishing-roller</td>
<td>202.4</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>621.3</td>
</tr>
</tbody>
</table>
The time rate of each phase is shown in Fig. 11. Both Expert and Non-expert have spent much time on phase 11. Expert spent 36.2% of the whole working hours on phase 11. On the other hand, Non-expert spent no less than 56.4% on phase 11.

![Fig. 11 Time rate of each phase](image)

### 4.2 Motion analysis

First, angular variation of the right elbow joint with a roller during impregnating glass-mat with resin was compared (Fig.12). These data was computable from the coordinate data of three points consisting of a wrist, an elbow, and the shoulder. While expert’s angular variation of his elbow joint was large, non-expert didn’t almost have angular variation.

![Fig.12 Comparison of right elbow joint angle during impregnating glass-mat with resin between expert and non-expert.](image)

Furthermore, displacement of the position both subject’s right shoulder marker (Z-axis direction) was compared (Fig.13). While displacement of expert’s right shoulder marker was large, non-expert didn’t almost have displacement.

![Fig.13 Comparison of position on the right shoulder marker (Z-axis direction) between expert and non-expert.](image)

Next, change of velocity and acceleration on the right hand marker are shown in Fig 14.

![Fig.14 Comparison of velocity and acceleration on the right hand marker during impregnating glass-mat with resin between expert and non-expert.](image)
Expert's velocity was more than twice as fast as non-expert. Moreover, Expert's stroke of roller was longer about twice than Non-expert's.

On the other hand, from comparison of acceleration, there is no big difference between expert and non-expert.

It seems that a motion of expert's smooth right arm originates in crookedness and expansion of elbow joint and shoulder. Moreover, it seems that expert's work posture hardly gives a burden to the body.

4.3 Eye movement analysis

Analysis of the blink and the look-at-point was conducted in the “finisher process” which was also a process of the last check. The number of blink and the average interval time of the blink in the phase 10 and the phase 11 are shown in table 3.

| Table3 Results of number of times of blink and average interval time of blink |
|---------------------------------|-----------------|-----------------|-----------------|
|                                 | Number of times of blink (number) | Average interval time of blink (sec.) |
| Phase                           | 10               | 11              | 10               | 11              |
| Expert                          | 30               | 19              | 2.3             | 9.8             |
| Non-expert                      | 72               | 276             | 1.1             | 2.7             |

Although the working hours of the phase 11 are shorter than the phase 10, the number of times of an expert's blink is decreasing conversely. As for the average interval time of blink, expert and non-expert showed the tendency for the phase 11 to become long.

In the phase10, expert's look did not move with his roller and expert was gazing at some fields of the mold (elliptical portion of Fig.15). On the other hand, Non-expert’s look was moving with his roller (Fig.16). In the phase 11, Expert was gazing at the corner of the mold (the standup portion from a bottom plane: dashed line portion of Fig.15), and his look was not moving with his roller. Non-expert had same tendency, but his look was not maintained at the fixed position as compared with Expert’s (Fig17).

Therefore, the above-mentioned results have suggested that expert’s centroid moved smoothly.

Fig.15 Look-at-points during finishing-process

Fig.16 Comparison of look-at-point at plane part during surface finishing between expert and non-expert.

Fig.17 Comparison of look-at-point at standup-parts during surface finishing between expert and non-expert.
4.4 Dimension stability

Next, the dimensional stability of the obtained specimen was compared. It turns out that experts have high dimensional stability clearly as Fig.18 and 19 show. Fig.18 shows the mimetic diagram which developed cross-sectional observation, and Fig.19 is the graph which showed thickness distribution. It turns out that Expert's thickness distribution is narrow focusing on 1.95 mm in thickness (CV:7.96%). On the other hand, thickness distribution of Non-expert is about 1.7 times large compared with Expert (CV:13.41%). Moreover, sectional photograph is shown in Fig.20. Expert's thickness is constant irrespective of vertical plane and convex part. On the other hand, the unevenness of thickness is seen in the convex part by which Non-expert is made difficult on fabrication operation, and the circumference of it.

And relationship between degree of skill, thickness, and dimensional stability (coefficient of variation for thickness) is shown in Fig. 21 and 22. It is suggested clearly that how to use a roller has influenced dimensional stability. Moreover, in definition of degree of skill, it is clear that how to use a roller is one of the important items.
Finally, the surface of samples that fabricated by Expert and Non-expert was observed (Figure 23). These data was obtained using micrometer. It turns out clearly that Expert’s surface is more uniform and close to the ideal thickness (1.90mm).

4.5 Mechanical property

Next, mechanical property of the obtained specimen was compared. The result of tensile strength in each specimen is shown in Fig. 24 and 25. Moreover, photographs of destructive crack of specimen after tensile test are shown in Fig. 26 and 27.

In addition, as for the tensile test, ten specimens were carried out in each sample.
Next, relationship between degree of skill, tensile strength and coefficient of variation for tensile strength are shown in Fig. 28 and 29. This result shows that there is correlativity with strong relation between degree of skill and mechanical properties. In particular, in the coefficient of variation for tensile strength, there is a big difference between Expert and Non-expert. Furthermore, it was suggested that mechanical properties are also closely related to how to use the roller (directivity, number of times, load, etc.) which is one of the measures of degree of skill. From now on, the data of two or more subjects who have various years of experience is investigated, and the relationship between degree of skill and mechanical properties is considered in detail.

5 Conclusion

As a result of having investigated the influence of the skill on dimensions stability and mechanical properties thoroughly, a clear difference was shown. In addition, the reproducibility of dimensions and the mechanical properties is seen in an expert, and the stable quality at a high level is provided. It is suggested that the skill of the engineer in the HLU molding method is more important in quality, and the offer of the high-grade HLU product is enabled through this study.

Finally, it was revealed that the characteristic of composites was influenced by degree of skill. And a roller is used in HLU method to impregnate resin to reinforcement fiber. Thus, it is supposed that difference in use of this roller affects the interface characteristics.

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References
