An Investigation on Conversion from Tacit Knowledge to Explicit Knowledge in Hand Lay-Up Fabrication Method

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Abstract. Hand lay-up fabrication has been used for forming composite structures since ancient times as it can be performed as long as the mold, skills, and materials are available. Hence highly specialized control technique and the tradition of skill are required to ensure the consistent stability of product quality. In this study, the authors thus conducted a motion analysis experiment using hand lay-up fabrication experts as subjects. The experiment, seemingly a new and only attempt in Japan, quantified techniques that are not visibly apparent and considered to be tacit knowledge. The mechanical properties and dimension stability of samples were measured, and their relationships with the motions of experts were also evaluated. It was also suggested that highly specialized control techniques, the appropriate training of non-experts, and technical tradition are possible.

Keywords: Hand lay-up · Dimension stability · Motion analysis · Composites · Explicit knowledge

1 Introduction

In hand lay-up (HLU) fabrication work, the characteristics of the composite material will be usually the same regardless of which forming method is used as long as the reinforced substrate, reinforcement morphology, matrix resin, and volume content of reinforcing material are the same. Composite materials, particularly fiber reinforced plastics (FRP) made of fibers and resins, are basically formed by impregnating fibers with resin, i.e., replacing the air contained in fibers with resin. With the HLU technique, rollers are used to impregnate reinforced fibers with resin. Consequently, the impregnation method is expected to contribute to changes in the properties of the interface formed. To review the effects of different roller use in the HLU technique on the mechanical properties of the composite structure, an experiment was conducted to analyze the process of work and investigate the relationships with mechanical strength and dimension stability of the structures built in craftsmen (experts, intermediates, and

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non-experts) specializing in making bathtubs using the HLU technique, who were asked to create FRP structures.

2 Methodology

2.1 Subject Persons

The subjects consisted of a total of five craftsmen ranging from an expert with 25 years of experience to one with only one year of experience. In this experiment, the craftsman with 25 years of experience is defined as expert, one with only one year of experience as non-expert, and those in between as intermediates. Table 1 shows the biological data of the subjects.

2.2 Experimental Protocol

FRP laminate molding using the HLU technique was analyzed. Figure 1 shows the size of the mold used in this experiment: length of 415 mm, width of 1,600 mm, and height of 50 mm.

2.3 Materials

The mold surface was pre-coated with a gel coat (white) of 0.5 mm in thickness, after which lamination was carried out using the HLU technique. Glass fiber chopped strand mat (380 g/m2) was used as the reinforced substrate, and isophthalic unsaturated

Table 1. Biological data of subjects

Subject	Age	Career (year)	Height (cm)	Weight (kg)	Dominant-hand
Expert	48	25	171	52	Right
Intermediate-1	41	18	163	61	Right
Intermediate-2	45	15	175	63	Right
Intermediate-3	28	4	163	60	Right
Non-expert	29	1	164	52	Right

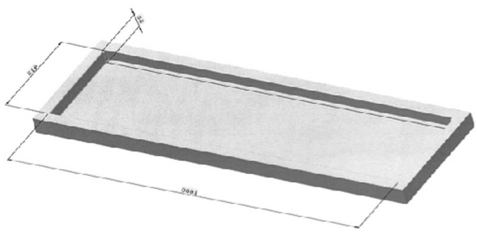

Fig. 1. Mold used in this study

polyester resin was used as the matrix. Cutting agent (MEKPO) was added to the resin at the ratio of 100 to 1.0. Two sheets of glass fiber chopped strand mats were used in the forming process.

2.4 Motion Analysis and Eye Movement Analysis

To measure the motion of the subjects, the MAC3D System (Motion Analysis Corporation) was used. The left side of Fig. 2 shows the motion analysis system. The infrared markers attached to the body of the subjects were captured using five cameras, and the collected information was sent to the PC as the 3D positional data of all the markers. The sampling frequency was set at 60 Hz. For eye movement, eye movement detector Talk Eye II (Takei Scientific Instruments Co., Ltd.) was used. The sampling frequency was set at 30 Hz. The right side of Fig. 2 shows the eye movement analysis system. The center camera was used to capture the field of vision of the subjects, while the cameras on both sides were used to capture eye movements.

2.5 Dimension Stability

To compare dimension stability between the expert and non-experts, the planar section and cross-sectional surface of the molded product obtained were observed (Fig. 3). A micrometer was used to measure the thickness. To compare the roughness of the surface of planar section, the 300 mm × 300 mm area in the center of the sample was measured. Subsequently, eight sections on the short side of the samples were cut out to observe the thickness distribution of the cross-section.

2.6 Mechanical Property

To evaluate mechanical property, twenty 150 mm × 30 mm specimens were sampled from the FRP molded product alternately in the lengthwise direction, as shown in Fig. 4. Two types of specimens were prepared: 10 with a drilled hole (φ = 10 mm) and 10 without a drilled hole. Because the drilled hole is easily damaged due to the

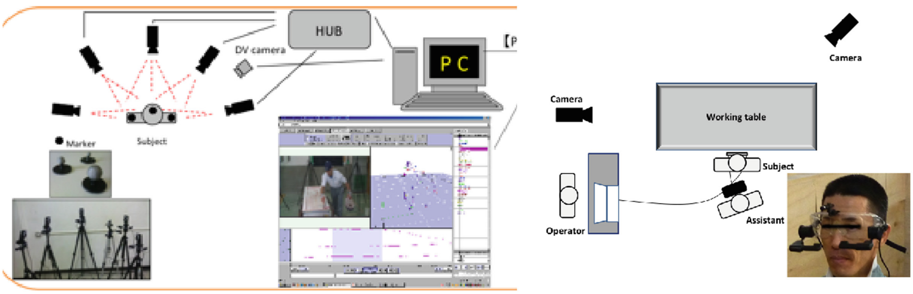

Fig. 2. Motion analysis and eye movement measurement systems in this experiment

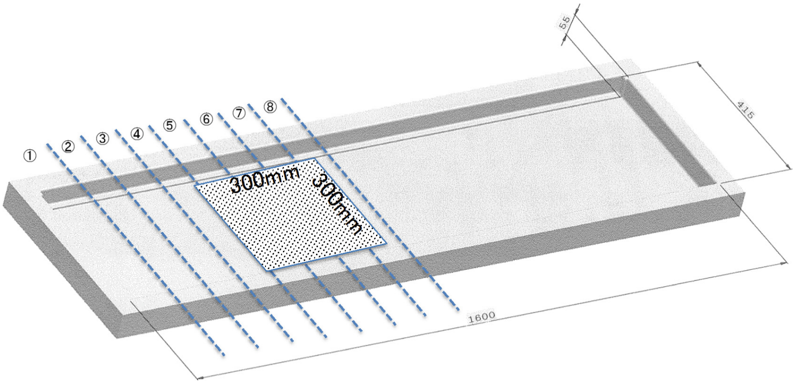

Fig. 3. Observation of dimension stability

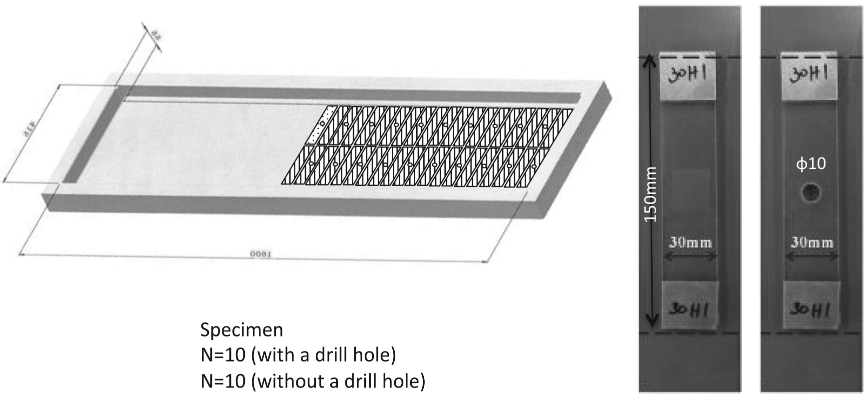

Fig. 4. Sampling of specimens for tensile testing

concentration of stress, there existed some difference from the data of the non-porous specimens. However, punching must be carried out for attaching parts, etc. for products in the actual uses of FRP structures in the automotive and aerospace areas. In this experiment, strength tests using porous specimens were also conducted to evaluate the actual uses of FRP structures. The test conditions were inter-chuck distance of 80 mm, and crosshead speed of 1 mm/min.

3 Results and Considerations

3.1 Process Analysis

The analysis of the work process of HLU molding among craftsmen with different careers found that the work process can broadly be divided into three:

Process 1: Setting glass substrate.
Process 2: Impregnation and defoaming using a roller.
Process 3: Surface finish using a finishing roller.

Particular for process 3, the work time and method of using the roller differ greatly according to the craftsman, which is suggested to characterize the HLU technique. For this reason, comparison was made focusing on process 3.

3.2 Motion Analysis and Eye Movement Analysis

The results of the motion and eye movement analyses carried out on each subject for process 3 are shown below. First, the point of regard (POR) (right eye) and operations were compared among subjects in process 3. Figure 5 compares how the expert and non-expert use the roller in the short-side direction. The left photos represent the expert while the right photos represent a non-expert. During the movement in the short-side direction, POR and the center of gravity is consistent regardless of the movements of the roller in the expert (left), suggesting the movements of the roller and the load are stable. On the other hand, the POR of the non-expert (right) moves when the roller moves, and the center of gravity also moves to and fro. This suggests that the stability of the roller movement and load are poorer in the non-expert than the expert.

Figure 6 traces the movements of the right eye POR of different subjects. The charts clearly demonstrate that only the POR locus of the expert moves in a narrow range.

The POR variation of the expert is small. The stable-POR movement is unique to the expert, independent of career. The expert is estimated to check the finish of the molded product through experience, touch, sound, etc.

Figure 7 compares how the expert and non-expert use the roller in the long-side direction.

The left side photos represent the expert while the right side photos represent the non-expert. The movements in the long-side direction were observed to be similar to those in the short-side direction. Instead of following the movement of the roller, the expert (left) constantly looked ahead, and the to and fro variations of the center of gravity were limited. In contrast, the POR of the non-expert (right) moved together

Fig. 5. How to use a roller between expert (left) and non-expert (right): short-side direction

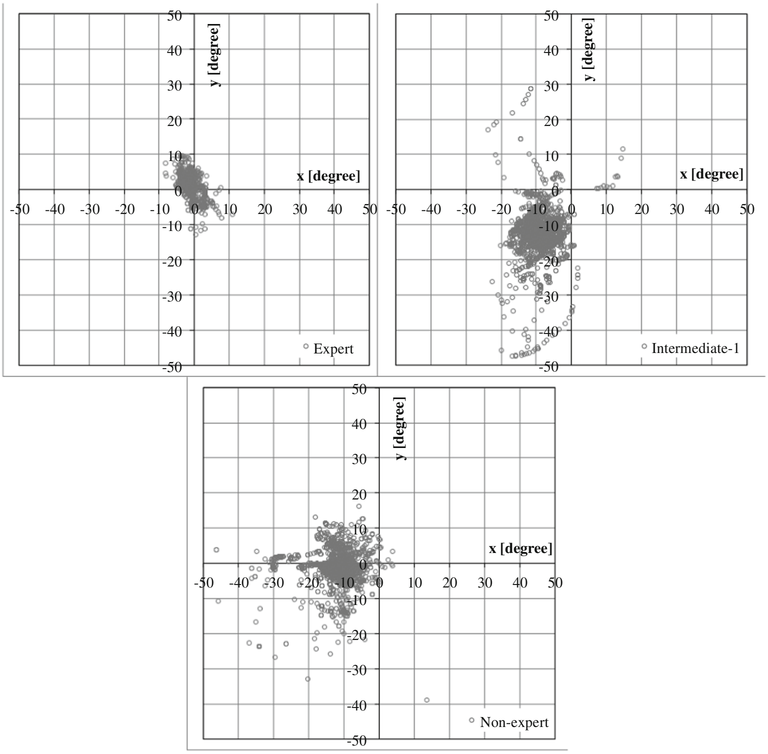

Fig. 6. Right-eye POR movements in subjects (process 3: during the motion in the short-side direction)

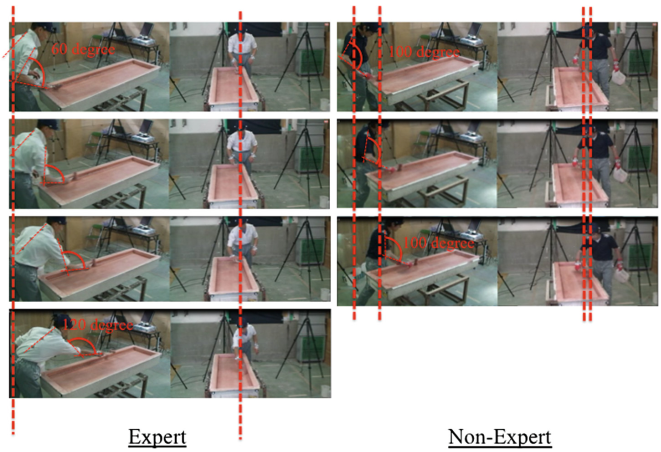

Fig. 7. How to use a roller between expert (left) and non-expert (right): long-side direction

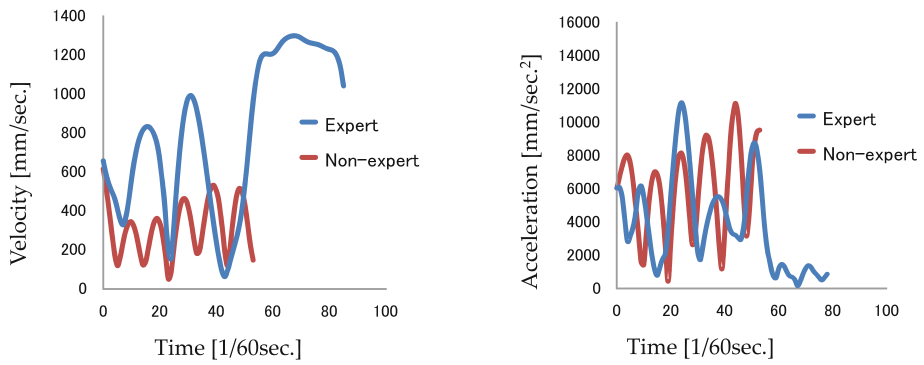

Fig. 8. Comparison of velocity and acceleration

with the roller, and the to and fro fluctuations of the center of gravity were about 2.5-fold larger than the expert. During the to-and-fro movements of the roller, the right elbow of the expert extended and bended in the range of 60–120 degrees. On the other hand, the elbow of the non-expert virtually did not extend or bend (about 100–110 degrees).

As a result, as shown in Fig. 8, the roller speed of the expert was about two times faster than that of the non-expert. However, the acceleration rate was almost the same between the two, presumptively because of the smooth extension and bending movements of the right elbow in the expert.

Furthermore, the expert held the handle of the roller from the top so that force is applied when pulling the roller. In fact, it was found later in interviews with the subjects that the expert tend to concentrate more on pulling than pushing the roller. On the other hand, the non-expert was found to hold the handle of the roller from below upwards so that force is applied when pushing the roller. This is thought to have resulted in the marked difference in the extension/bending of the right elbow and speed of the roller between the expert and non-expert.

3.3 Dimension Stability

Figure 9 shows the distribution of the thickness in the short-side direction. It is apparent that thickness is consistent (1.9 mm) for the expert even in the elevation surface and R convex section, while it is not consistent for the non-expert in the convex section and its vicinity, which are thought to be difficult to form. The convex section was about 15 % thinner, while the vicinity of the convex section was about 15 % thicker than the average thickness.

These results suggest that how the roller is used clearly affects the thickness of the planar, elevation, and R convex sections, in other words the stability of the shape. In addition, it is evident that how the roller is used is closely related to operations that define "career," as shown in Fig. 10.

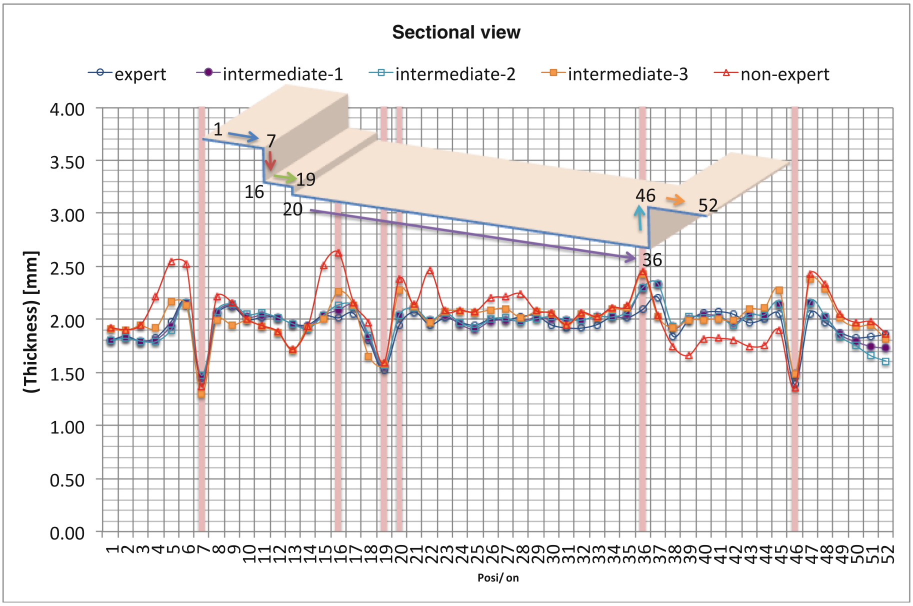

Fig. 9. Sectional view

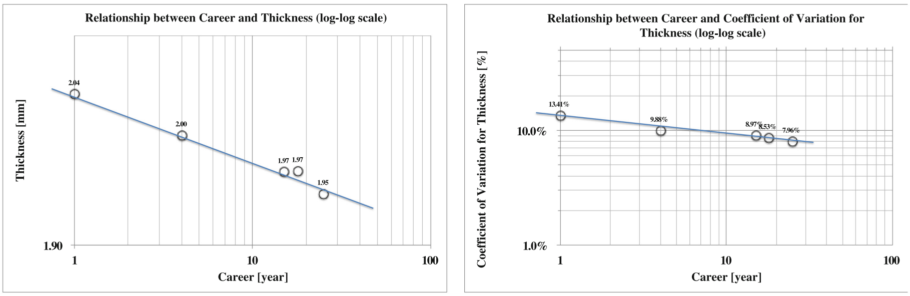

Fig. 10. Relationships between career and thickness or the coefficient of variation

3.4 Mechanical Property

The effects of career on mechanical property were investigated. Figure 11 shows the tensile strength and coefficient of variation, with respect to career, in specimens with and without drilled holes.

First, comparison of the tensile strength of specimens between the expert and non-expert indicates that it is about 15 % higher in the expert's specimen. In addition, a strong correlation was found between career and tensile strength (coefficient of correlation: 0.99 (NHT), 0.92 (OHT)). On the other hand, correlation was weak in the coefficient of variation (coefficient of correlation: –0.87 (NHT), –0.65 (OHT)).

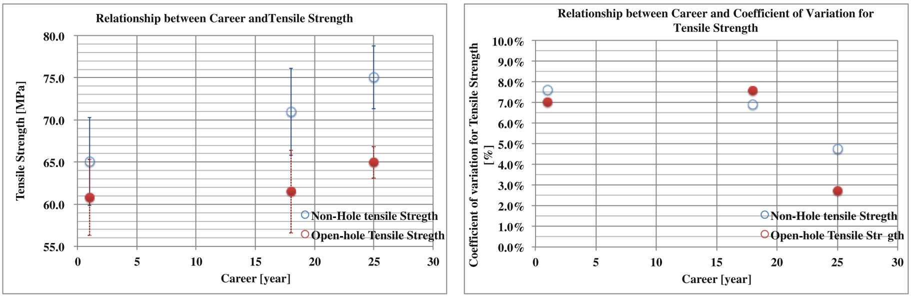

Fig. 11. Relationships between career and tensile strength or the coefficient of variation

4 Conclusions

The findings suggest that the craftsman's career has a large effect on mechanical property in the HLU technique because FRP demonstrated different characteristics even if the same reinforced substrate, reinforcement morphology, matrix resin, and volume content were used. The results also suggest a close relationship between how the roller is used (e.g., direction, frequency, and load), which is a measure of career, and mechanical property.

Characteristics of the expert can be summarized as follows:

1. Smooth movement of the right elbow during roller movements*.
2. POR is consistent and is independent of the movements of the hand.
3. Center of gravity is consistent and stable.
4. Holding the roller handle from the top and focusing on pulling movements.

*As force is evenly distributed, the coefficient of variation of the thickness and mechanical strength is estimated to be small.

Furthermore, it was found that the above four points can be incorporated into the educational tools of non-experts and intermediates, sharply reducing the skill acquirement time. The inclusion has also increased the fun and joy of skill acquirement among them.

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