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Facing Evaluation on Vacuum Assisted Resin Infusion (Vari) Co-Cured Sandwich Composites: Inlet and Outlet Comparison

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Abstract

Sandwich composites are preferred in marine or aerospace applications due to their superior specific flexural properties. Low-cost, high-quality sandwich composites can be produced using the co-curing method with the Vacuum Assisted Resin Infusion (VARI) manufacturing technique. However, manufacturing composites with VARI results in thickness variation between the resin inlet and vacuum outlet, thus affecting the uniformity of mechanical properties. This study evaluated the facing properties variation of sandwich composites fabricated using the VARI co-cure method with different numbers of facing plies. Sandwich composites were fabricated with carbon fiber/epoxy and PVC foam using the VARI co-cure method with central linear infusion. The thickness, fiber volume fraction, and tensile properties of the facings were evaluated at the resin inlet and the vacuum outlet for comparison. The sandwich composites were successfully fabricated using the VARI co-cure method. The facing properties between the resin inlet and vacuum outlet have variations of 2,6-15.0 % in thickness, 0.7-5.5 % in fiber volume fraction, 3.6-6.2 % in tensile modulus, and 5,7-35.17 % in tensile strength. Upper facings tend to have a higher property variation than lower ones. As the number of facing plies increases from 2 to 6, the thickness variation and the fiber volume fraction also increase, resulting in a higher variation in tensile modulus and strength.

Keywords: sandwich composite, vacuum-assisted resin infusion, co-cure, thickness variation, tensile properties.

1. Introduction

Sandwich composites are preferred in many industries, such as marine or aerospace applications, because of their high flexural strength and stiffness-to-weight ratio (Kazmi, Govignon, and Bickerton 2019; Manalo, Aravinthan, and Karunasena 2013; Yalkin, Icten, and Alpyildiz 2015). A sandwich composite consists of two thin, high-strength facings (aluminum or fiber-reinforced plastic) and a lightweight core (balsa wood, foam, honeycomb) placed between the facings (Caliskan and Kemal Apalak 2020; Menta et al. 2012). The facings are mainly responsible for flexural strength and stiffness by resisting the bending loads in either tension or compression. Meanwhile, the core resists the shear/compressive loads and enhances the flexural properties without significantly increasing the weight (Caliskan and Kemal Apalak 2020; Manalo et al. 2013). A combination of facings properties, core properties, and the interface bonding between them will determine the properties of the structural sandwich(Yalkin et al. 2015).

One of the manufacturing processes that is commonly utilized in the low-volume production of large sandwich composites and fiber-reinforced plastics laminates is Vacuum-Assisted Resin Infusion (VARI)(Hancioglu, Sozer, and Advani 2020; Jhan, Lee, and Chung 2012; Kazmi et al. 2019). The VARI process can produce composites with high quality at low production costs

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(Kazmi et al. 2019; Menta et al. 2012; Yenilmez, Senan, and Murat Sozer 2009). The advantage of the VARI method is the possibility of producing a sandwich composite in a one-step process or co-curing technique to reduce production costs and time (Menta et al. 2012; Rusnáková and Žaludek 2018). On the other hand, the drawbacks of the VARI process are the difficulties in predicting the resin flow to avoid incomplete impregnation and controlling small dimensional tolerances (Modi et al. 2007; Yokozeki, Yamazaki, and Kobayashi 2015).

Several studies have focused on thickness variation during the VARI process. Tackitt and Walsh monitored surface displacement during infusion using linear variable differential transformers (LVDTs) and concluded that the VARI process results in thickness gradients due to resin flow patterns and compaction pressure distribution, which lead to gradients in fiber volume fraction and mechanical properties (Tackitt and Walsh 2005). Yenilmez et al. also studied the effects of pressure distribution on part thickness during the VARI process. Their results showed that pressure redistribution during the infusion and post-filling stages significantly influenced thickness uniformity between the resin inlet and vacuum outlet (Yenilmez et al. 2009). Yokozeki et al. further investigated the compaction behavior and resin pressure in the VARI process and proposed a method to control resin content and fiber volume fraction to achieve desired mechanical properties (Yokozeki et al. 2015). These findings highlight the complex interactions between resin flow, compaction pressure, and mold geometry that result in thickness variation, influencing the final composite's mechanical properties and dimensional accuracy.

VARI is a closed mold manufacturing process using a solid mold and a flexible vacuum bag on the other side of the mold. The pressure gradient is formed during the infusion due to the increase in local resin pressure depending on the flow front. It counteracts the compaction pressure of the flexible vacuum bag, thus resulting in thickness variation as a function of the distance between the inlet and outlet (Li et al. 2008). The variation in thickness will affect the uniformity of the achievable fiber volume fraction and the properties of the final product (Kazmi et al. 2019; Yokozeki et al. 2015). However, the previous research mentioned is mainly focused on thickness variations in laminate composite manufacturing using VARI, while research on thickness variations in sandwich manufacturing with VARI is still limited, especially for the co-curing method. The main objective of this research is to evaluate the thickness and tensile properties variation between the inlet and outlet of facings sandwich composites fabricated by VARI co-cure manufacturing methods.

2. Methodology

2.1. Materials

The upper and bottom facings consist of carbon fiber fabrics and epoxy resin. The carbon fiber was twill 2/2 HDC-524 3K with an areal weight of 240 g/m^2. The epoxy resin was a mixture of Eposchon EPR-174 resin with Eposchon EPH-555 hardener, with a weight ratio of 2:1, and 10 % thinner Eposchon EPD Z-8 was added to the mix. The core materials were PVC foam (divinycell H080), with a density of 80 kg/m3 and a thickness of 20 mm, with perforation and groove machining at the upper and bottom surfaces. All the constituent materials were obtained from PT. JUSTUS KIMIARAYA, Indonesia.

2.2. Sandwich Fabrication

The VARI set-up consists of a glass mold with two dry preforms on top (upper facing) and bottom (lower facing) of the core material. Peel ply and infusion mesh were laid on top of the upper dry preforms, and a sealed vacuum bag covered the whole set-up. Peel ply insertion

between the dry perform and core was also placed to facilitate facing separation for testing. The whole set-up was vacuumed for 1 hour, and the vacuum pressure was monitored in order to detect a leak in the set-up. The dimension of the sample was 90 cm long and 25 cm wide. The vacuum outlet was placed at both edges, while the resin inlet was located at the center, separated by 500 mm between the resin inlet and the vacuum outlet. The sandwich composites were fabricated using a central linear infusion in a one-step VARI infusion. The schematics of the VARI set-up can be seen in Figure 2-1. The resin and hardener were mixed using a manual stirrer for about 5 minutes at room temperature (55% relative humidity), then degassed for 15 minutes prior to infusion. The resin inlet was closed when the infusion had completed or after the resin had thoroughly wetted the entire dry preforms. The vacuum was maintained for 1 hour after the resin inlet was closed, and the sample was then cured for 24 hours at room temperature. The facings varied by 2, 4, and 6 plies to evaluate the effect of different plies on the properties of the facings. A CNC cutting machine cut the sandwich samples into test specimen shapes. The upper and lower facings were first separated from the core using a thin blade before facings characterization.

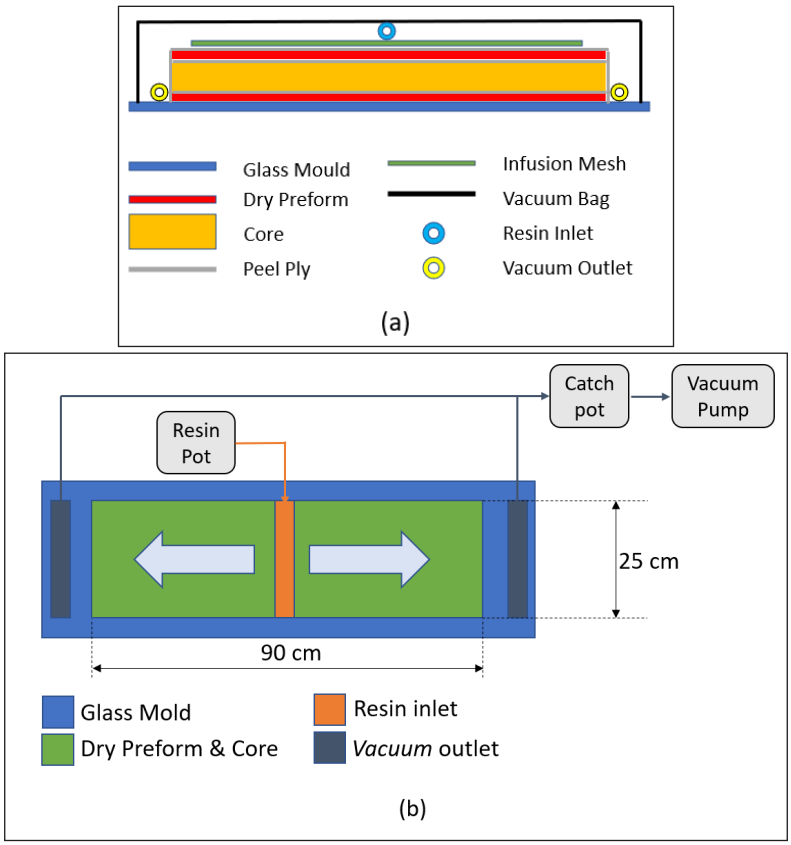


Figure 2-1: The VARI set-up schematics, (a) side view and (b) top view

2.3. Facing Characterization

The physical and mechanical properties, such as thickness, density, fiber volume fraction, void content, tensile modulus, and tensile strength of upper and lower facings for 2,4, and 6 plies, were evaluated. A Mitutoyo micrometer was used to measure the thickness distribution along the facing length at 100 mm intervals (5 points along the width for every 100 mm position). The density, fiber volume fraction, and tensile evaluation were conducted near the resin inlet and the vacuum outlet of each facing using three specimens for each location.

Densimeter Kern ABJ-NM/ABS-N was utilized to measure the density of facings according to ASTM D792 with 40 x 40 mm specimens. The identical specimens were used for fiber and void volume fraction testing according to ASTM D3171 test method I procedure A (matrix digestion using nitric acid). A universal testing machine, Orientec co. Ltd, UCT-5T, was used to perform the tensile test according to ASTM D3039. The size of the specimens was 150 x 15 mm, and the crosshead speed was set to 2 mm/min. Table 2-1 lists the codes used to identify each variation of the facing specimen.

Table 2-1: Facing Codes

Facing Codes	Side	Number of Plies
2U	Upper/Vacuum Bag	2
2L	Lower/Glass Mold	2
4U	Upper/Vacuum Bag	4
4L	Lower/Glass Mold	4
6U	Upper/Vacuum Bag	6
6L	Lower/Glass Mold	6

3. Result and Discussion

3.1 Thickness Distribution and Variation of Facings

Figure 3-1 shows the thickness profile of the upper and lower facings for 2, 4, and 6 plies resulting from the thickness distribution along the length of the sample. In general, the thickness at the vacuum outlet is greater than that at the resin inlet, indicating that the facings obtained from VARI co-cure sandwich fabrication also exhibit a thickness variation, as in laminate fabrication using VARI. It was also observed from Figure 3-1 that the thickness variations of the facings increased with the increasing number of plies. However, some researchers found that the thickness variation in laminate fabrication has a different thickness profile, with the thickness at the resin inlet being higher than the vacuum outlet due to the increasing resin pressure at the resin inlet during the infusion process (Li et al. 2008; Rubino and Carlone 2019; Yenilmez et al. 2009). The cause of the different thickness profiles is the placement of the resin inlet and vacuum outlet; even though other researchers also utilized linear infusion, the resin inlet was positioned at the edge, and the vacuum outlet was positioned at the other edge, resulting in one-directional linear flow. On the other hand, in the central linear infusion, the resin flows in two directions to both sides of the edge, and the resin pressure at the resin inlet is distributed, resulting in a thickness profile that resembles the thickness profile produced by radial infusion (Tackitt and Walsh 2005). The post-filling condition can also contribute to the resulting thickness profile (Kazmi et al. 2019; Rubino and Carlone 2019). The vacuum was continued for 1 hour after the infusion had completed, and the resin inlet was closed, thus providing the opportunity to distribute the resin inside the mold toward the vacuum outlet.

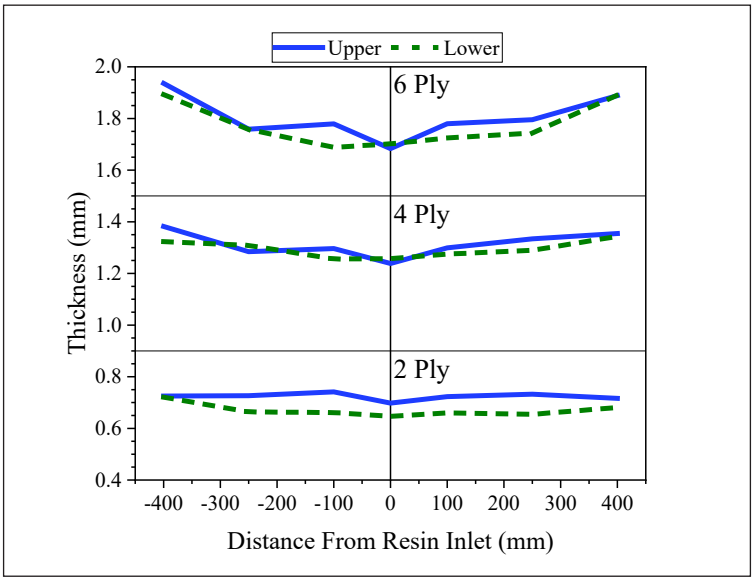


Figure 3-1: Thickness Profile of Upper and Lower Facings for 2, 4, and 6 Plies

The average thickness and variation between the resin inlet and vacuum outlet of the upper and lower facings are shown in Table 3-1. The thickness variations at the vacuum outlet compared to the resin inlet ranged between 2.6% to 15% for the upper facings and 5.3% to 11.2% for the lower facings. The upper facings exhibit greater thickness variation and a thicker average thickness than the lower facings. This happened because the upper and lower faces had different mold rigidity, which affected the compaction pressure. The upper facings were contacted with a flexible mold, the vacuum bag; meanwhile, the lower facings were placed directly on the glass mold. The upper and lower facings also had different resin flow velocities and patterns during the infusion (Halimi et al. 2013; Jhan, Lee, and Chung 2011; Jhan et al. 2012), thereby resulting in different thickness variations. Moreover, it was found that the facings' thickness variance increased as the number of plies increased from 2 to 6.

Table 3-1: Average Thickness and Thickness Variations of Upper And Lower Facings.

Facing	Average Thickness (mm)	Thickness Variation (mm & %)
2U	0.723 ± 0.018	0.018 (2.6 %)
2L	0.670 ± 0.031	0.034 (5.3 %)
4U	1.313 ± 0.056	0.143 (11.6 %)
4L	1.293 ± 0.41	0.066 (5.2 %)
6U	1.803 ± 0.90	0.253 (15 %)
6L	1.771 ± 0.084	0.191 (11.2 %)

3.2. Fiber Fraction and Void Content of Facings

Figure 3-2 shows the fiber volume fraction of upper and lower facings at the resin inlet and the vacuum outlet. There is a variation in the fiber volume fraction of around 0.003-0.025 (0.7 - 5.5%) between the resin inlet and the vacuum outlet. The fiber volume fraction at the vacuum outlet is lower compared to the resin inlet, corresponding to a thicker thickness at the vacuum outlet. However, the fiber volume fraction of two plies upper facing is likely similar at the vacuum outlet and resin inlet, corresponding to lower thickness variation as shown in Table 3-1. The lower facings have a higher fiber volume fraction (1.1-1.9%) than the

upper facings, resulting from a thinner average thickness (Table 3-1). It was observed that the thicker facings have a lower fiber volume fraction and that the fiber volume fraction variations between the resin inlet and vacuum outlet correlate to the thickness profile from Figure 3-1. Furthermore, Figure 3-2 shows that the 6 plies facings have higher fiber volume fraction and variation than the 2 plies facings. Yokozeki et al. investigated carbon fiber laminates with 6, 12, and 18 plies and also discovered a higher fiber volume fraction at higher numbers of plies (Yokozeki et al. 2015).

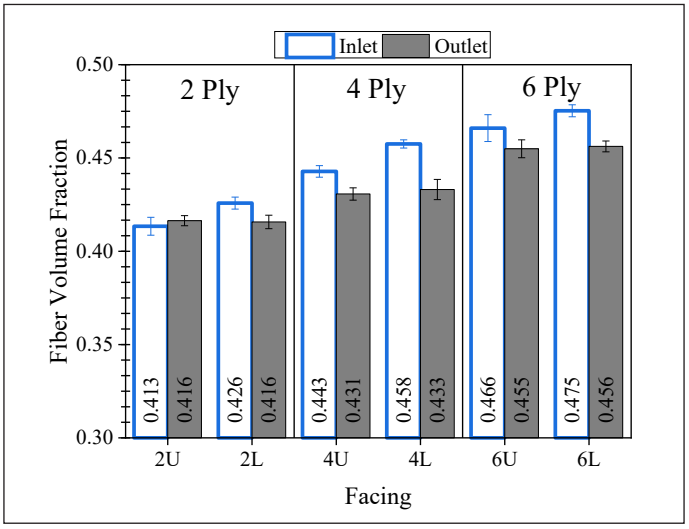


Figure 3-2: Fiber Volume Fraction of Upper and Lower Facings at The Resin Inlet and Vacuum Outlet

The void content of the upper (2U-6U) and lower (2L-6L) facings at the resin inlet and vacuum outlet is shown in Table 3-2. The void content in all facing samples is between 0.13% and 1.36%, representing a relatively low volume fraction. There were no significant variations between resin inlet and vacuum outlet in terms of void content, nor between upper and lower facings.

Table 3-2: Void Content of Upper and Lower Facings at The Resin Inlet and Vacuum Outlet.

Facing	Void Volume Fraction (%)	
	Inlet	Outlet
2U	0.21 ± 0.30	0.23 ± 0.02
2L	1.36 ± 1.20	1.20 ± 0.20
4U	0.16 ± 0.08	0.13 ± 0.14
4L	2.08 ± 1.56	2.36. ± 0.35
6U	1.19 ± 0.12	0.97 ± 0.40
6L	0.60 ± 0.41	0.14 ± 0.04

3.3. Tensile Modulus of Co-cured Sandwich Facings

The tensile modulus of the upper and lower facings is shown in Figure 3-3. The tensile modulus at the resin inlet (41.88-52.31 GPa) was higher compared to the vacuum outlet (40.34-49.86 GPa), resulting in a 3.7-6.2% variation relative to the resin inlet. The upper facings were likely to have lower tensile modulus than the lower facings, especially at the resin inlet, due to higher average thickness and lower fiber volume fraction. All 6 plies facings also have higher tensile modulus compared to the 4 plies facings, and the 4 plies facings have higher tensile modulus than the 2 plies facings. It was demonstrated that a higher fiber volume fraction with lower thickness results in a higher tensile modulus, and thickness

variations also correspond to tensile properties variations. However, the upper facings have lower variations of fiber volume fraction (0.7-2.7 %) and tensile modulus (3.7-5.0 %) between resin inlet and vacuum outlet compared to lower facings variations of fiber volume fraction (2.3-5.5 %) and tensile modulus (4.7-6.2%), which is the opposite of upper and lower facings thickness variations. This is due to the thickness variations being calculated between the lowest and highest thickness, which was measured by point interval. On the other hand, the fiber volume fraction and tensile modulus were evaluated using a specific area of specimens that represent a larger region of resin inlet and vacuum outlet.

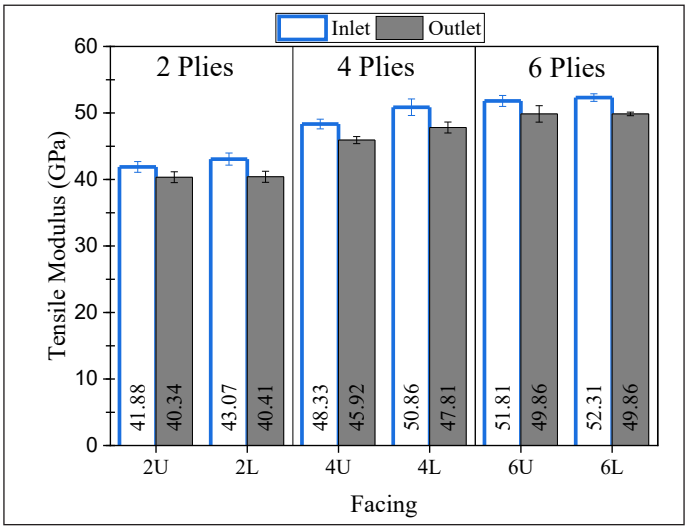


Figure 3-3: Tensile Modulus of Upper and Lower Facings at The Resin Inlet and Vacuum Outlet

3.4. Tensile Strength of Co-cured Sandwich Facings

Figure 3-4 represents the tensile strength of the upper and lower facings at the resin inlet and vacuum outlet. For the lower facings, the tensile strength at the resin inlet (455-521 MPa) is higher compared to the tensile strength at the vacuum outlet (429-485 MPa), while the tensile strength at the resin inlet (320-392 MPa) was significantly lower than the tensile strength at the vacuum outlet (433-490) for the upper ones.

Relative to the fiber volume fraction, the tensile strength of the upper facings at the resin inlet was very low due to the placement of the resin inlet on top of the upper facings, which deformed the dry preforms and generated a defect with spiral tube shape in the final part, as shown in Figure 3-5. The tensile strength variations between the resin inlet and vacuum outlet for the upper facings were 14.3-35%, whereas for the lower facings were 5.7-7.1 %. The tensile strength of the lower facings was higher compared to the upper ones, and it also rose as the number of facing plies increased, indicating that the tensile strength of the facings follows the same general trend as the fiber volume fraction and thickness.

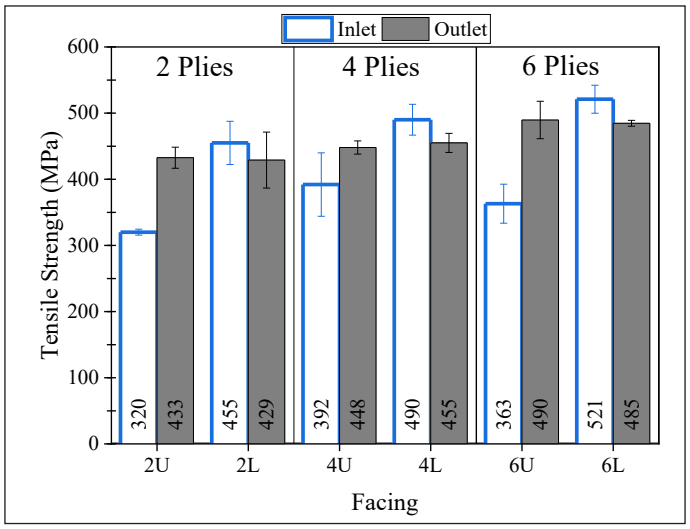


Figure 3-4: Tensile Strength of Upper and Lower Facings at The Resin Inlet and Vacuum Outlet



Figure 3-5: Surface Defect of Upper Facings at The Resin Inlet

4. Conclusions

The facings of the sandwich fabricated by VARI co-cure resulted in thickness variations between the resin inlet and vacuum outlet. In general, facings at the resin inlet had lower thickness (2,6-15.0 %), higher fiber volume fraction (0.7-5.5 %), higher tensile modulus (3.6-6.2 %), and higher tensile strength (5,7-35.17 %) compared to the outlet. Compared to the lower facings, the upper facings had a thicker average thickness, lower fiber volume fraction, lower tensile modulus and strength, and higher thickness and tensile strength variations, but lower fiber volume fraction and tensile modulus variations between the resin inlet and vacuum outlet. The resin inlet and vacuum outlet of the upper facings had 2.6-15% thickness variations, 0.7-2.7 % fiber volume fraction variations, 3.7-5,0 % tensile modulus variations, and 14.3-35.0 % tensile strength variations. Yet, the variations between the resin inlet and vacuum outlet were 5.2-11.2 % in thickness, 2.3-5.5 % in fiber volume fraction, 4.7-6.2 % in tensile modulus, and 5.7-7.1 % in tensile strength for the lower facing. Increasing the number of plies from 2 to 6 resulted in an increase in thickness, thickness variations, fiber

volume fraction, tensile modulus, and tensile strength. The different plies of the facings did not significantly affect the variations of fiber volume fraction, tensile modulus, and tensile strength between the resin inlet and vacuum outlet.

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6. Contributorship Statement

RA designed the method, conducted the experiment, analyzed the results, and prepared the manuscript; HJ and RW supervised the research and reviewed the manuscript.

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