REPAIR EFFICIENCY OF RESIN INFUSED SCARF REPAIR TO MARINE SANDWICH STRUCTURES

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SUMMARY

A vacuum-assisted resin infusion technique is used to repair the damaged skin and core of a GRP/Balsa sandwich. Flexural effectiveness of the repair both in tension and compression are evaluated for two repair configurations and repair systems. Prediction analyses were undertaken to study the failure mode and good experimental agreement was found.

Keywords: repair efficiency, composite repair, sandwich structures, 4 point flexure, scarf repair, vacuum –assisted resin infusion

INTRODUCTION

Fibre reinforced composite sandwich structures have been increasingly adopted in marine vessels for their high stiffness-to-weight and strength-to-weight ratios. These structures undergo various damages during service and depending upon the damage type, location, size and severity, appropriate repair techniques are performed. Any permanent repair technique adopted has to restore the full integrity of the damaged composite sandwich structure. Damage can occur to one skin (Type A damage), to one skin and core (Type B damage) or both skin and core (Type C damage).

Extensive studies are carried out on the repair of composite laminates e.g.[1] but very less on sandwich structure repair e.g. [2]. Moreover, of these repair studies, most research concentrations are towards honeycomb or foam based sandwich structures. GRP/Balsa sandwich structures are the potential candidate in UK marine applications (navy) and there is a need to fully understand the repair method and its effectiveness in these structures. Various repair configurations such as overlap patch, scarf repair, step repair are adopted for the repair of the sandwich structures and amongst them scarf repair technique has provided the greater efficiency e.g. [3]. Apart from repair configurations, production technique also plays an important role in improving the efficiency. Hand laid with vacuum consolidated scarf repair technique is widely adopted for marine structures [4]. The hand lay up repair generally results in an inconsistent repair, low volume fraction and high percentage of voids within the bond line that eventually lead to low load-carrying capabilities of the repaired component. Greater care has to be taken to produce a good quality repair.

In recent years, the vacuum assisted resin infusion (VARI) production technique is gaining wider acceptance in marine industries for composite laminate and composite sandwich structure fabrication due to reduced styrene emission, one step process, reduced fill time, more consistent, higher volume fraction and lower void content leading to higher mechanical properties e.g.[5, 6].

Combining the scarf repair configuration and the modern production technique of vacuum assisted infusion, vacuum assisted resin infused scarf repair (VARI-SR) is adopted in this research to repair the Type B damage (damage to single skin and also to core) of the marine sandwich structure. The repair of damaged core is by core replacement and repair of skin is similar to the process adopted for composite laminates. Two repair configurations of scarf repair (scarf angle 3° and 6°) and two repair systems (resin system similar to parent and different to parent) are employed for the repair of skin. For core replacement, vacuum infused full replacement of similar material and density core is used.

Undamaged and repaired sandwich beams are loaded in four-point bending with repair both in tension and compression and the effectiveness of the repair technique is evaluated. The failure mode for various repair configurations is observed. Preliminary studies of analytical predictions and Finite element analysis using ANSYS are performed for parent sandwich structures to study the failure modes and compared with experimental observation.

MATERIALS AND METHODS

Materials

Sandwich panels of size 550 x 550 mm, with 2.5 mm GRP (E glass/epoxy) skin and 9.52 mm D-100 end grain balsa core are manufactured using vacuum infusion process. Both the face skins are constructed from Formax 800 E- glass triaxial [0/-45/45] reinforcement layer and Prime 20 LV epoxy resin . Formax 800 is a satin weave fabric with an areal weight of 819 gsm and the layer thickness of approximately 0.6 mm. Four layers are used to form a stacking sequence of $[0/-45/45]_{2s,}$ providing an overall thickness of 2.5 mm. Repaired sandwich panels are fabricated with 3° or 6° scarf angle and repaired with prime 20 LV resin (same as parent) or Ampreg 22 resin (different to parent). The properties of face laminate, prime 20 LV resin and the core material can be obtained in tables 3 and 4.

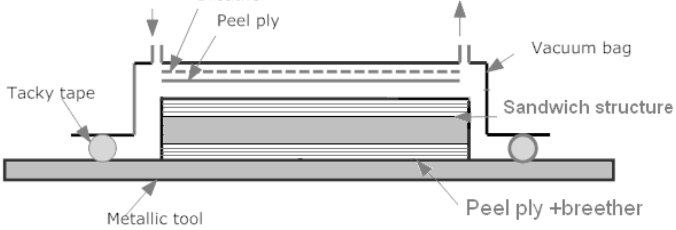

Figure 1 : Schematic diagram of the fabrication of parent sandwich structure

Fabrication of undamaged sandwich structure

The procedure for fabrication of parent sandwich using vacuum assisted resin infusion (VARI) technique can be found elsewhere e.g. [5, 6]. Figure 1 shows the schematic diagram of the fabrication of parent sandwich structure.

Repair procedure

Repair to core and singe skin is investigated in the present work. Damage to skin and core of size 60 mm is simulated by fabricating the sandwich structure and repairing them using various repair configurations such as 1:20 scarf (3° angle) or 1:10 scarf (6° scarf angle) and using various repair system such as prime 20 LV (epoxy repair resin similar to parent resin) or Ampreg 22 (epoxy repair resin different to parent resin). To maintain the stiffness of the parent and repair patch, plies identical to parent $[0/45/-45]_{2s}$ is used for the repair. Single overlapping ply, similar to parent material [0/45/-45], is used to enhance the strength and protect the scarf tip [1] and an overlap length of 20 mm is used.

Fabrication of damaged sandwich structure

A damaged sandwich with 60 mm defect is fabricated as follows: Required reinforcements are placed to form lower skin on the molding plate. Preconditioned balsa core is then cut and placed above lower skin leaving 60 mm in the middle (in assumption that it is the core defect of 60 mm and is been removed for repair) on either side. For the upper skin, scarfed face is produced. The plies are placed one over other, such that each successive plies are shorter than previous plies as required for the various scarf angles(3° or 6°), leaving the mid 50 mm core defect. Placing the successive layer 20 mm shorter than previous layer provides scarf angle of approximately 3°. This was followed by resin infusion using Prime 20 LV epoxy resin. The cured damaged sandwich structure is then demolded and is now ready for repair.

Repairing the damaged sandwich structure

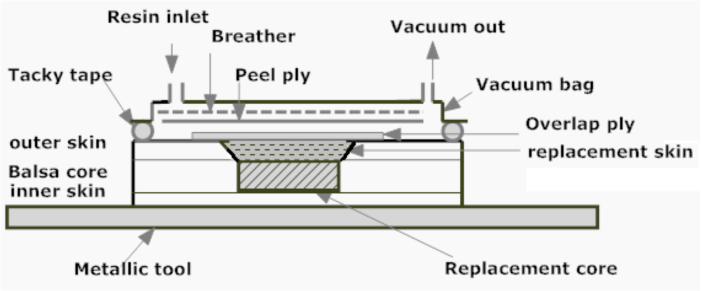

Figure 2 : Resin infused scarf repair of sandwich structure

The damaged sandwich structure is abraded of extra resins at the defect corners, the outer face properly scarfed and cleaned with acetone. Now this structure resembles a sandwich structure which has the damage removed, is scarfed and waiting for repair. The following outlines the procedure of repairing the damaged structure, figure 2: the whole damaged structure is placed on the metallic tool and the core of required defect length is replaced. Mild tolerance is left on both sides of the replaced core for resin fill. The damaged scarfed upper skin is replaced with the layers of same material with each successive layer longer than the previous layer as required for various scarf angle. Placing each successive layer 40 mm longer than previous layer would provide the replacement skin for the damaged 3° scarf upper skin. One extra overlap layer is placed extending 20 mm beyond the extend of all damage. Vacuum bagging procedure is continued. Once vacuum is established, the resin mixture (either Prime 20 LV mixture (same as parent) or Ampreg 22 (different to parent)) is introduced to the resin inlet. Resin flows from the inlet to outlet infusing the replaced core and skin. The panel is allowed to cured, demolded and cut into required size sandwich coupons. Figure 3 shows the parent sandwich and the vacuum assisted resin infusion scarf repaired (VARI-SR) sandwich coupons.

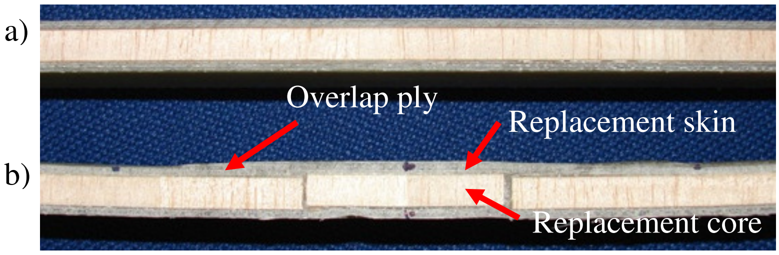

Figure 3 : (a) Parent sandwich coupons and (b) repaired sandwich coupons

FOUR POINT FLEXURE TEST

The undamaged VARI panels are cut into sections of 230 x 50 mm and 550 x 50 mm and are mechanically tested in 4 point bending according to ASTM C393-62 with the loading points located at two quarter-span points. Span lengths of 180 mm and 460 mm were used for undamaged panel to study the failure mode, Figure 4.

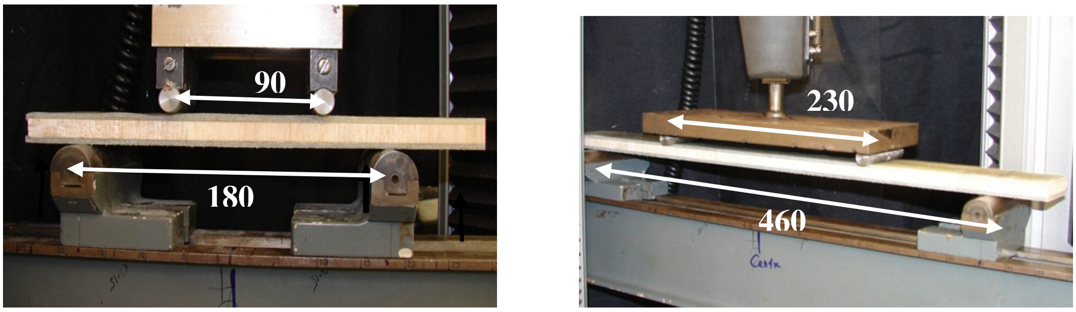

Figure 4: Four point flexure of undamaged sandwich (a) Span length 180 mm (b) Span length 460 mm

Higher span lengths are not considered due to limitations of fabricating very long VARI sandwich panels in available laboratory facilities. Tests are performed in an Instron 5569 testing machine in displacement control at a rate of 3.6 mm/ min. Load and crosshead displacement are recorded using computerised data logging system (Bluehill software) until a large drop in the load associated with the failure is noted and the failure modes are observed.

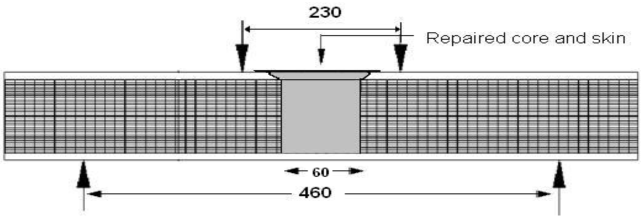

Figure 5: Details of four point flexure of the repaired sandwich structure with repair in compressive side

The repaired panels with different repair scarf angles and different repair systems are tested with the repair alternately in tension and compression using a span length 460 mm, as shown in figure 5. The location of the repair is within the inner span load. As for undamaged coupons, load and crosshead displacement are recorded until large drop in load is noted and the failure mode observed.

RESULTS AND DISCUSSION

Undamaged sandwich

The flexure behaviour of the undamaged VARI GRP/Balsa sandwich structure was experimentally studied by subjecting the coupons under two different span lengths (180 mm and 460 mm). Four specimens were tested for each span length. The flexure load vs. cross-head displacement of the undamaged specimens for two different span lengths, one each, is shown in figure 6. The coefficient of variation in the slope of load vs. deflection curve for all 180 mm span coupons are 7.01% and for all 460 mm span coupons are 1.1%. The failure load and the failure mode observed in the undamaged coupons are tabulated in Table 1.

Table 1: Failure load and failure mode of parent panel tested under various span lengths.

Span length, mm	Failure load, N	Load/width, N/mm	Face tensile (MPa)	Core shear (MPa)	Failure mode
180 span	5053.06 ±546.92	101.06 ±10.93	75.66 ±8.19	4.20 ±0.45	Core shear +slow skin-core debond
460 span	3857.33 ±414.79	77.14 ±8.29	139.84 ±11.37	2.99 ±0.296	Core shear +immediate skin-core debond

It was noted that the failure load of short span coupons is higher than the 460 mm span coupons. There is a large variation in the stiffness of the coupons. The possible reasons for the increase in failure load in short span is to be explored in prediction. All the specimens failed by means of core shear, between inner and outer supports. In short span (180 mm), core shear is slowly followed by upper skin-core debond extending towards either sides, see figure 7 a. In case of larger span (460 mm), it was immediately followed by skin-core debond, figure 7 b.

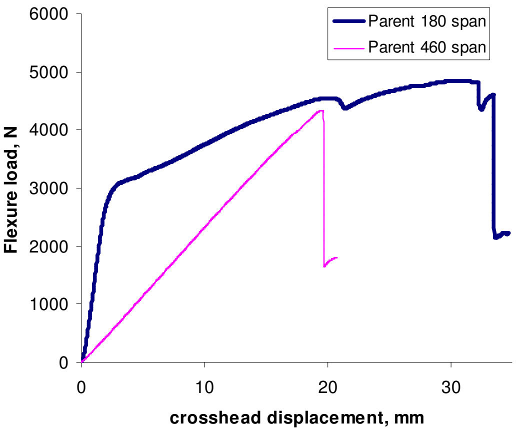

Figure 6: The flexure load vs. cross-head displacement of the undamaged specimen under different span lengths

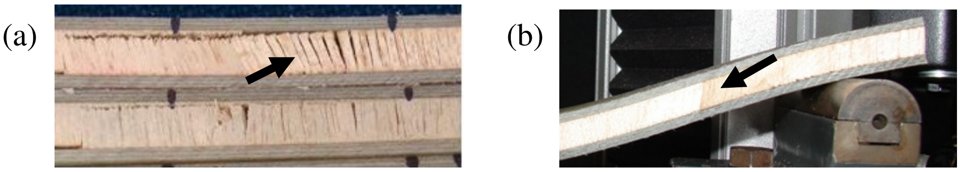
(a) (b)

Figure 7 : Failure mode observed in (a) Parent :180 span (b)Parent:460 span

Repaired sandwich

The VARI –SR sandwich coupons with different scarf angle (3° or 6°) repaired using different repair resin systems (Prime 20 LV epoxy or Ampreg 22 epoxy) are subjected to flexure loading with 460 mm span as indicated in the testing procedure. The testing was done with repair both in compression and tension. In case of the undamaged sandwich, tests in both sides are not considered as the sandwich is symmetrical with the same face sheet geometry and material. The experimental failure load obtained for the repaired panel is tabulated in Table 2 and the face tensile and core shear strength is calculated using the equation (2) and (4) respectively. The failure mode observed in all the repaired sandwich coupons is core shear between inner and outer supports, immediately followed by core-facesheet debonding, as noticed in the parent. The repaired core and skin remained intact with no sign of failure. The repair efficiency is calculated as in equ. (1)

$$\text{Repair efficiency} = \frac{\sigma_R}{\sigma_V} x100\,\% \qquad (1)$$

where σ_V is undamaged core shear strength and σ_R repaired core shear strength.

It can be seen from table 2 that all the repairs recovered more than 89% of the undamaged failure strength. The scarf angle 3°(1:20) and 6° (1:10) doesn't have much influence on the repair efficiency for this system at 460 span length. The repair resins used and the test with repair in compression and tension also doesn't have much influence in the repair efficiency taking into consideration the standard deviation involved. It was due to core shear failure, and not a failure at the face laminate. This clearly indicates that the repairs remain intact for this system and geometry when the span lengths are below a critical value. Further predictions are considered to find the critical span length needed to initiate failure in skin, so that true repair assessment could be carried out. Scaling factor considerations from previous study for the span length is also explored.

Table 2. Test results for repaired sandwich with repair tested in compression and tension.

	Repair in compression				Repair in tension (inverted)			
	Failure load, N	Face tensile streng-th (MPa)	Core shear streng-th (MPa)	Repair efficie-ncy %	Failure load, N	Face tensile streng-th (MPa)	Core shear streng-th (MPa)	Repair efficie-ncy %
Panel A	3857.33 ±414.79	139.84 ±11.37	2.99 ±0.296					
Panel B	3472.93 ±172.11	111.77 ±5.62	2.67 ±0.134	89.29	3630.20 ±365.78	117.56 ±11.84	2.81 ±0.283	93.97
Panel C	3552.98 ±350.48	115.05 ±11.34	2.75 ±0.271	91.97	3673.12 ±536.80	118.94 ±17.38	2.844 ±0.415	95.11
Panel D	3542.54 ±195.31	112.95 ±10.53	2.72 ±0.21	91.03	3652.52 ±501.05	117.71 ±9.74	2.80 ±0.28	93.64

where Panel A is undamaged sandwich, Panel B, Panel C is panel repaired with 1:10 scarf using same resin system and different repair resin system respectively and Panel D is panel repaired with 1:20 scarf using same resin system.

PREDICTIONS

Theoretical Prediction of undamaged sandwich

Sandwich beams under flexure loading undergo various failure mechanisms such as skin compressive/tensile failure, skin wrinkling; core shear failure, core tensile/compressive failure and skin-core debond. The failure loads for each mode are calculated using the following equations.

Face yielding [7, 8]],

$$P_f = \frac{\sigma_f t_f d}{CL} b \tag{2}$$

where C=1/8 for four point and C=1/4 for third point flexure loading.

Face wrinkling[8],

$$P_f = \frac{8 t_f d (E_f E_c G_c)^{\frac{1}{3}}}{L} b \tag{3}$$

Core shear[7],

$$P_f = 2\tau_c db \tag{4}$$

where σ = in-plane normal stress, τ = out-of plane shear stress, E = Young's modulus, G = shear modulus, t = thickness, L = span length, P = failure load, b = width, d= $(t_c + t_f)$ and subscripts f=face;c=core.

Table 3: Properties of face laminate [9] and Prime 20 LV epoxy resin [datasheet]

Material	Young's Modulus, Gpa	Shear Modulus, GPa	Poisson's ratio	Tensile strength, Mpa	Compressive strength, Mpa	Shear Strength, MPa
Face laminate	23.74	6.62	0.53	426.47	196.39	83.40
epoxy	2.97	-	0.4	69	55	40

The material properties considered for the predictions are provided in table 3 and 4. The failure load/unit width for different failure modes are calculated for GRP/balsa core sandwich using the above equation (2)-(4) and are plotted as a function of span length L, see figure 8. In GRP/Balsa sandwich structure, face wrinkling occurs at very high load or large span. Before face wrinkling, face yielding occurs. Hence face yielding and core shear are the predominate failure modes for the present geometry balsa sandwich structure. For this system, the sandwich would fail under core shear till it reaches about 1500mm span length. Face yielding then becomes the failure mode after about 1500 mm span length. To calculate critical span , equ (5) was derived from equ (2) and (4)

$$L_{cf} = \frac{\sigma_f t_f}{2C\tau_c} \tag{5}$$

Table 4: Properties of D-100 end grain balsa wood core [7]

Material	Density	In-plane tensile		Transverse tensile		In-plane compressive		Transverse Shear	
	(kg/m^3)	Modu -lus (GPa)	Streng -th (MPa)	Modu -lus (GPa)	Streng -th (MPa)	Modu -lus (GPa)	Streng -th (MPa)	Modu -lus (GPa)	Streng -th (MPa)
balsa	154	0.1	0.69	3.56	13	0.13	0.7	0.16	2.96

The calculated critical span for the system used is 1440 mm. This makes our experimental work clear on the core shear failure mode for 180 mm span and 460 mm span in undamaged coupons. For the Balsa core sandwich structure, core thickness has no influence on failure mode and only by changing the face-sheet material system and face thickness, the failure mode can be changed. When the experimental failure load was compared with the theoretical predicted load, it was noticed that the predicted core shear failure load for 460 mm span was 3700 N (calculated from P/b =74 N/mm in figure 8) and it agrees well with the experimental load of 3857.33 ±414.79 N. For 180 mm span, predicted failure load was 3700 N, but the experimental failure load was higher (5053.06 ±546.92 N). The reason behind the increase in failure load for lower span is still unclear.

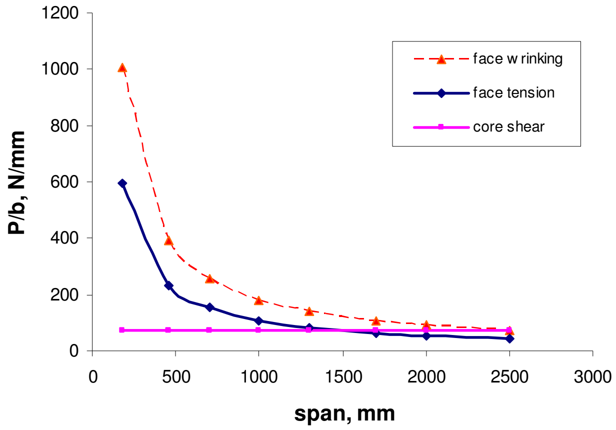

Figure 8: Failure mode for GRP/balsa sandwich under quarter point flexure loading.

Numerical predictions of undamaged sandwich

The flexure behaviour of undamaged sandwich was predicted preliminarily using commercially available finite element package, ANSYS. The model is constructed with adhesive line in between face laminate and core. The material properties as mentioned in table 3 and 4 are used for the face laminate, adhesive and core respectively. 2-D 8-Noded Structural solid elements are used.

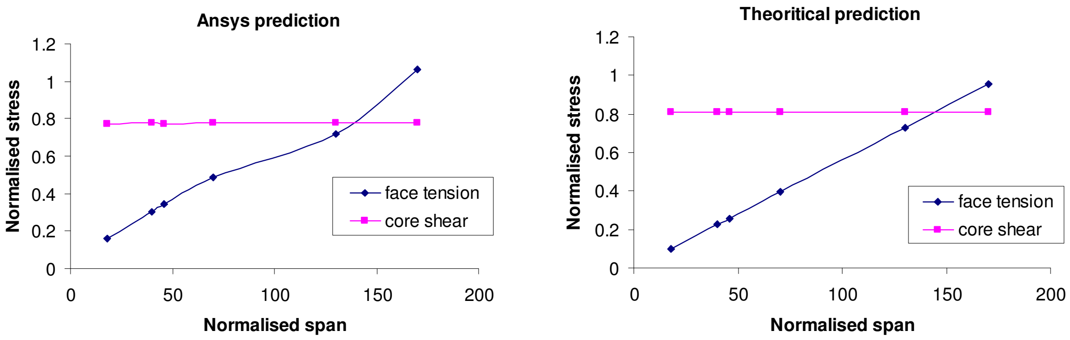

Figure 9. (a) Dominant failure mode prediction using FEA. (b) Dominant failure mode prediction using theoretical equations.

Non-linear analysis was conducted for different span lengths, to study the dominant stresses responsible for the failure. As theoretical design depicted two failure modes, face tension and core shear, these stresses are calculated in the ANSYS model at a failure load of 3000 N. The stresses obtained are normalised by their respective strength values and are plotted against normalised span (span length to core thickness) as shown in figure 9 (a), and theoretical prediction calculated using the equ. (2) and (4) is shown in figure 9 (b) for comparison. The failure mode predictions and the stress values agree well with both Ansys and theoretical predictions. Both the predictions indicate that the failure mode would change from core shear to face tensile only at about 1500 mm span length.

CONCLUSIONS

Four point flexure studies are conducted for GRP/ balsa core marine sandwich structure fabricated using vacuum assisted resin infusion technique. The failure mode in the balsa core undamaged structure was core shear at two different span lengths (180 mm and 460 mm) and it was predicted both theoretically and using FEA that the failure mode will be changed from core shear to face tension above a critical span. The critical span for the system used in this study is predicted to be 1440 mm.

The process and the procedure for repairing Type B damage (damage to single skin and core) in sandwich structure using vacuum assisted resin infusion scarf repair technique is provided in detail. The repair process used in the present study was found to be successful and most of the repair regained above 90% of the undamaged flexure strength. The failure mode observed in the repaired sandwich is core shear between inner and outer span load with no indication of failure in the repaired region. For 460 mm span lengths, the repair effectiveness was almost same for different repair configurations (3° and 6° scarf angle) and different repair resins. True repair assessment could not be conducted due to the large panel fabrication limitations in laboratory. The true repair assessment will be carried out by fabricating the large panel in industry.

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