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# Curing parameter optimization of the adhesive film in honeycomb sandwich structures through mechanical performance

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ABSTRACT

In this investigation, honeycomb sandwich structures were manufactured for aerospace structural applications. The composite material of carbon fiber and epoxy matrix was utilized as the facesheet of sandwich structures while Nomex® honeycomb acted as the core material. For the bonding of facesheet with core, an epoxy-based adhesive film was used. To optimize the curing parameters of the adhesive film, a set of four curing temperatures, i.e., 100°C, 110°C 120°C and 130°C, and two curing times, i.e., 2h and 3h were applied. The prepared sandwich structures were tested under a three-point bend test to investigate the maximum mechanical properties. It was found that the temperature of 120°C with the curing time of 2h provided the maximum mechanical properties and thus was selected as the optimized curing parameters of adhesive film.



## 1. Introduction

Among a variety of aerospace materials, honeycomb sandwich structures enjoys a special place due to their light weight and high mechanical performance. The honeycomb sandwich structures usually have honeycomb core sandwiched between two facesheets. Not only high mechanical properties, better acoustic and thermal insulation are other characteristics of honeycomb sandwich structures (Avery and Sankar, 2000).

In honeycomb sandwich structures, facesheets bear the bending load and the honeycomb core carries the shear load and thus improves the stiffness of the structure. Furthermore, an increase in the thickness of honeycomb core improves the flexural strength and stiffness of sandwich structures. Although, foam and wood are also utilized as core materials in sandwich structures, the better stiffness, crushing strength and fatigue properties of honeycomb core gives a special preference over other cores structures (Cantwell and Davies, 1994). A range of materials are used for honeycomb cores from metallic to polymeric and ceramics including aluminum, fiberglass, aramid, carbon and alumina. In contrast, facesheets are made of aluminum, steels and composite materials.

The joining of facesheets with honeycomb core is very critical with respect to the overall performance of honeycomb sandwich structures. For the joining of facesheet with honeycomb core, fasteners and adhesives as paste and films are used (Johnson and Sims, 1986). The adhesive attaches the facesheets to the honeycomb core so as to efficiently transfer the stress from one facesheet to another through the honeycomb core (Giglio et al., 2012). Therefore, an effective joint between the facesheets and honeycomb core promotes the capability of a sandwich structure to carry load. When bending load is applied, shear stresses are developed at the interface, i.e. between the core and the face sheet. The shear stress could debond the two structural parts of the sandwich structure leading to a structural failure. The applications of a good adhesive can prevent such a disaster. Therefore, the joint formed at the interface by an adhesive material significantly influences the mechanical performance of a honeycomb sandwich structure (Johnson and Sims, 1986).

The evaluation of interfacial mechanical properties is required prior to implementation in aerospace structures (Johnson and Sims, 1986). Three-point bend test is one of the most suitable mechanical tests to explore the shear and flexural rigidities of sandwich structures. A range of mechanical properties such as facing bending strength, core shear strength, core shear modulus and transverse shear rigidity can be evaluated by the

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three-point bend test. In addition to evaluation by experimentation, the numerical investigation of three-point bend test has also been executed on sandwich honeycomb structures containing aluminum facesheets (Giglio et al., 2012). In addition to three-point bend test, application of force through air-blast on sandwich structures is another approach of mechanical property evaluation (Langdon et al., 2012).

Besides mechanical characterization, the detection of failure mechanism of sandwich structures is also required to understand the damage process (Fan et al., 2010). In this respect, the absorption of crushing energy of sandwich structures has also been estimated during failure (Velecela et al., 2007) together with the understanding of interfacial fracture in sandwich structures (Cantwell et al., 1999). It is the reason that a variety of mechanical property characterization techniques have been devised to explore the core-facesheet adhesion.

In the present work, honeycomb structures were characterized using three-point bend test to discover their mechanical properties after joining the facesheets and the honeycomb core with an epoxy-based adhesive. The material of facesheets was carbon fiber epoxy matrix composite while Nomex® honeycomb was used as the core. The compression bonding technique was used to cure the adhesive film using four curing temperatures and two curing times. The mechanical property data was acquired from three-point bend test and based upon it, the curing parameters of the adhesive film were optimized.

## 2. Experimental

Honeycomb sandwich structures were manufactured by using Nomex® hexagonal phenolic impregnated honeycomb core of 20mm and cell size 5.5mm, carbon fiber epoxy matrix composite facesheets of 1mm thickness and an epoxy-based adhesive film of thickness 0.35-0.45mm as bond material. The honeycomb core was procured from Armicore Composite Company, China while the adhesive film of brand name CNMEHP-69B was provided by CNME International, China. The composite facesheets were prepared indigenously using two-dimensionally woven carbon fabric as reinforcement and epoxy resin as matrix, as discussed elsewhere (Farooq et al., 2017).

To manufacture honeycomb sandwich structures, the adhesive film was applied between the facesheets and the honeycomb core and compressed under load for bonding. Twi metallic plates were used for compression while increasing the temperature to specified values. A total of eight set of sandwich structures were prepared by applying four curing temperatures, i.e., 100°C, 110°C, 120°C and 130°C for two curing times of 2h and 3h.

The specimens extracted from the eight sandwich structures were characterized under three-point bend test as per the specification of ASTM standard C393/C393M. The specimens of rectangular shape with dimensions of 203.2mm length, 76.2mm width and 22mm thickness were tested. In addition to maximum load borne by the specimens, four other mechanical properties were evaluated by three-point bend test including (a) core ultimate shear stress, (b) facing bending stress, (c) core shear rigidity, and (d) core shear modulus.

## 3. Results and discussion

The load-displacement curves of composite honeycomb sandwich panels containing epoxy-based adhesive film cured at 100°C, 110°C, 120°C and 130°C for 2h are shown in Fig. 1. It can be seen that by increasing curing temperature from 100°C to 110°C and then 120°C, the peak load values increased, i.e., 2.39KN, 2.65KN and 2.89KN, respectively.

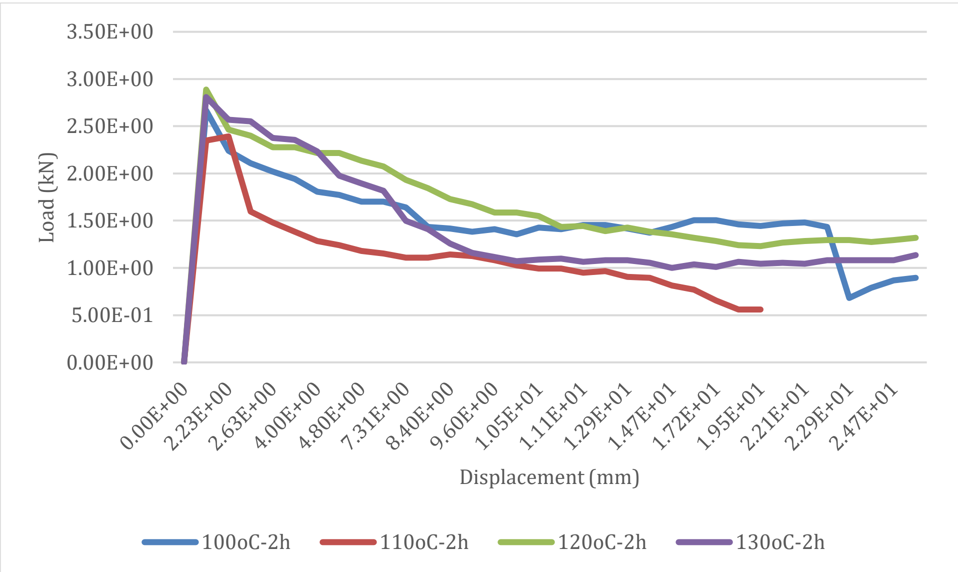


**Fig. 1:** Load-displacement curves of composite honeycomb sandwich panels cured at 100°C, 110°C, 120°C and 130°C for 2h

However, further increase in temperature to 130$^{o}$C resulted in a decrease in peak load value, i.e., 2.80KN. As a result, the mechanical properties followed the same trend, as shown in Fig. 2. The facing bending strength increased continuously from 100$^{o}$C to 110$^{o}$C and then 120$^{o}$C, i.e., 58.4±2.4MPa, 64.7±3.3MPa and 70.6±5.6MPa but at 130$^{o}$C the value decreased to 68.4±4.1MPa (Fig. 2a). A similar trend was followed by core shear strength (0.75±0.05MPa, 0.83±0.07MPa, 0.90±0.09MPa, 0.87±0.06MPa), core shear modulus (25.5±1.1MPa, 35.3±2.1MPa, 41.1±4.2MPa, 39.4±2.6MPa) and transverse shear rigidity (39.5±2.0KN, 59.2±2.7KN, 69.0±4.5KN, 66.1±3.7KN) at curing temperatures of 100$^{o}$C, 110$^{o}$C, 120$^{o}$C and 130$^{o}$C, respectively, as shown in Figs. 2b, 2c, and 2d.

The load-displacement behavior of composite honeycomb sandwich structures manufactured at four different temperatures for 3h subjected to three-point bend test is shown in Fig. 3. It is interesting to observe that a continuous decrease in the peak load values was observed with an increase in temperature.

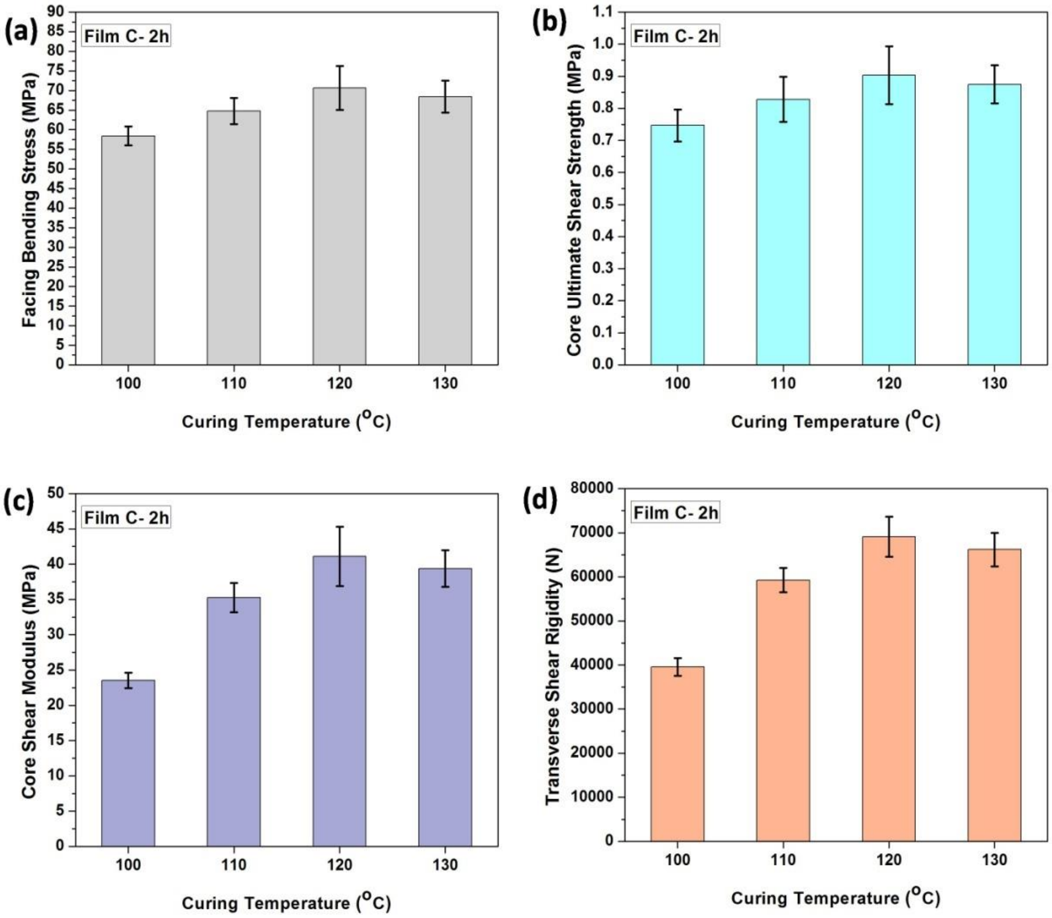


**Fig. 2:** Properties of sandwich panels cured at 100$^{o}$C, 110$^{o}$C, 120$^{o}$C and 130$^{o}$C for 2h (a) facing bending strength (b) core shear strength (c) core shear modulus (d) transverse shear rigidity

The mechanical properties calculated from three-point bend test results are shown in Fig. 4. The facing bending strength decreased continuously with an increase in curing temperature, i.e., 65.4±5.2MPa, 63.7±3.2MPa, 62.7±1.7MPa, 58.1±1.1MPa), as shown in Fig. 4a. A similar trend of the continuous decline in other mechanical properties was witnessed: core shear strength values, i.e., 0.84±0.07MPa, 0.82±0.05MPa, 0.80±0.06MPa, 0.74±0.02MPa), core shear modulus values, i.e., 33.6±2.1MPa, 32.7±1.6MPa, 31.3±0.8MPa, 30.3±2.7MPa, and transverse shear rigidity values, i.e., 56.4±2.4KN, 55.0±2.5KN, 53.9±2.7KN, 50.6±3.4KN, at 100$^{o}$C, 110$^{o}$C, 120$^{o}$C and 130$^{o}$C, respectively (Figs.4b, 4c, and 4d).

Fig. 5 shows the cross-sectional images of specimens of two honeycomb sandwich structures showing maximum (120$^{o}$C for 2h) and minimum (130$^{o}$C for 3h) mechanical properties and their magnified images are also presented in Fig. 6. The filleting property of adhesive film is clearly noticeable in the honeycomb sandwich panels. The specimens which were cured at 120$^{o}$C for 2h showed optimum mechanical properties and possessed local indentation failure as indicated in Fig. 5a and Fig. 6a. The increased mechanical performance of this specimen is due to the adequate flow of adhesive film at the optimized curing parameters thereby promoting coating effect on the honeycomb cell walls along with the efficient bonding characteristics to transfer load from carbon fiber epoxy matrix composite facesheets to honeycomb core. The specimen shown in Fig. 5a and Fig. 6b revealed minimum peak load and the failure mode observed in these honeycomb sandwich panels was core crushing and tearing. From Fig. 5a and Fig. 6b, unsymmetrical flow of adhesive film can also be witnessed. Only optimized curing temperature of adhesive films offer better mechanical properties of the honeycomb sandwich structures and any change in the curing parameters can severely affect the mechanical performance of honeycomb composites along with the change in the failure mode of honeycomb core.

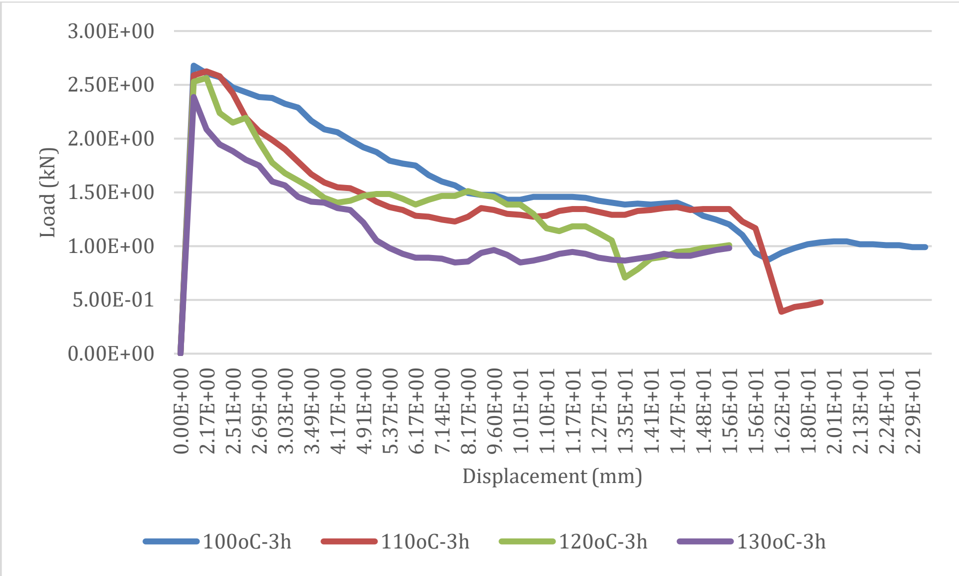


**Fig. 3:** Load-displacement curves of composite honeycomb sandwich panels cured at 100ºC, 110ºC, 120ºC and 130ºC for 3h

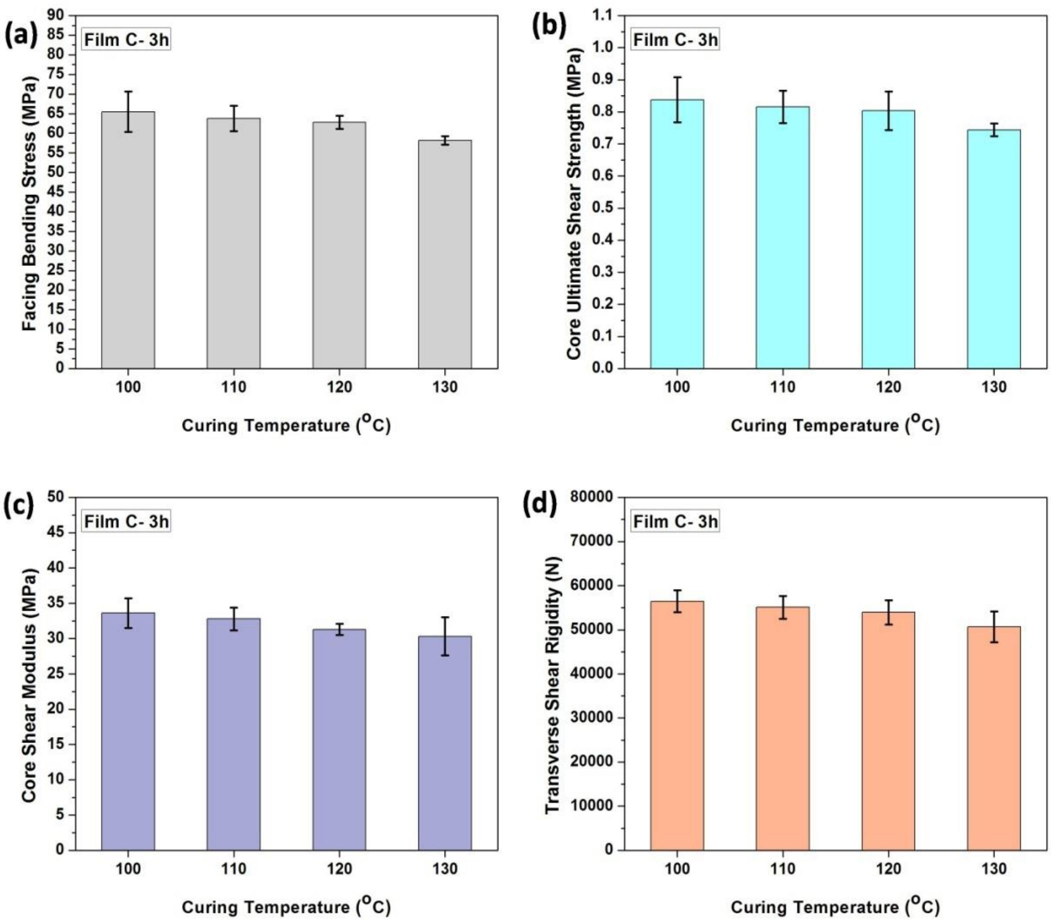


**Fig. 4:** Properties of sandwich panels cured at 100ºC, 110ºC, 120ºC and 130ºC for 2h (a) facing bending strength (b) core shear strength (c) core shear modulus (d) transverse shear rigidity

The experimental data and the photographic observation of the specimens of honeycomb sandwich structures indicate that the both curing temperature and curing time of adhesive film influence the mechanical performance of honeycomb sandwich structures. The optimized curing parameters for honeycomb sandwich structures are 120°C for 2h, whereupon the sandwich structures showed maximum mechanical properties that may be due to the formation of suitable and symmetrical fillets (Okada and Kortschot, 2002; Rion et al., 2008). Moreover, at these parameters, the honeycomb structures demonstrated the maximum peak loads prior to the deformation of the core and failure of upper facesheet. The associated mechanical properties of sandwich structures at these parameters were also higher than other sandwich structures. At the optimized curing parameters, the adhesive film constitutes a required fillet between the honeycomb core and the face sheets, which ultimately transfers the load efficiently from one facesheet to another through the honeycomb core.

It is to be noted that the rise in temperature assists to the flow of adhesive film toward the walls of honeycomb core and thus make adhesive film less viscous. However, the increased temperature stimulates the curing of adhesive film. It was the result that the mechanical properties of honeycomb sandwich structures increased by increasing the temperature from 100°C to 120°C at 2h after preparing a symmetrical fillet while the further rise in temperature to 130°C resulted in the premature curing of the adhesive film without the formation of a uniform fillet. Along with temperature, the elongated curing time also deteriorated the adhesive fillet. As a result, it can be seen that by increasing the curing time from 2h to 3h, the mechanical properties decreased and at 3h the properties further decreased when temperature increased from 100°C to 130°C.


**Fig. 5:** Cross-sectional view of sandwich panels (a) cured at 120°C for 2h (b) cured at 130°C for 3h


**Fig. 6:** Magnified view of sandwich panels (a) cured at 120°C for 2h (b) cured at 130°C for 3h

## 4. Conclusion

Honeycomb sandwich structures were produced by compression technique using facesheets of carbon fiber epoxy matrix composites and core of Nomex® honeycomb. An epoxy-based adhesive film was used to bond the facesheets with the honeycomb core. A range of adhesive film curing temperatures and curing times were applied to optimize the curing parameters. In total, a set of eight honeycomb sandwich structures were prepared and tested under three-point bend test. The sandwich structure containing adhesive film cured at 120°C for 2h demonstrated the maximum load bearing capability and associated mechanical properties, and hence selected as the optimized adhesive film curing parameters. The formation of an adequate fillet after the sufficient flow of adhesive towards the walls of honeycomb and thus the effective bonding between the facesheet and honeycomb core were found to the possible reasons of improved mechanical performance of honeycomb structure processed in optimized curing parameters. The sandwich structure showing maximum mechanical properties revealed the minimum damage in comparison to sandwich structures processed with other curing parameters.

## Compliance with ethical standards

## Conflict of interest

The authors declare that they have no conflict of interest.

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