Experimental Analysis for Bending Response of Toughened Interface Honeycomb Sandwich Plate

Rahul Kumar[1]*, Ashok Magar*[2*]*, Nikhil M Kulkarn*[3]*, Achchhe Lal*[4]

[1]Department of Mechanical Engineering, SOE, P P Savani University, Surat, India
[2]Department of Mechanical Engineering, N. K. Orchid College of Engineering and Technology, Solapur, India
[3]Faculty of Engineering and Technology, Parul Institute of Engineering and Technology, Parul University, Vadodara, India
[4]Department of Mechanical Engineering, SVNIT, Surat, India

Abstract. This research work examines the bending response of honeycomb core sandwich plates that have toughened and untoughened interfaces that are reinforced by using layers of Kevlar fibers. Three-point flexural strength tests were performed to determine how the interface was altered to affect the mechanical performance. The results showed that the interface toughening increases the maximum loading load and the toughness as a whole of the sandwich specimens at all loading rates considered. Failure mechanisms were studied by means of scanning electron microscopy, and the impact of interfacial reinforcement was observed. There were great improvements in kevlar reinforced specimens and the maximum load and energy absorption of kevlar reinforced specimens had improved by about 41 and 38.5 percent respectively.

1 Introduction

Corrugated and honeycomb sandwich structures are being implemented in aerospace, marine, and wind energy use as the ratio of stiffness to weight and strength to weight is excellent. The bending and in-plane loads are mainly resisted by the fiber-reinforced composite (FRC) face sheets with the honeycomb core supporting the shear stresses and inhibiting local buckling in such systems [1], [2]. Composite face sheets with aluminum honeycomb cores are very popular in different variants because they have high energy absorption capacity and good acoustic insulation [3]. The mechanisms of failures of honeycomb sandwich structures are still a topic of great research interest. Typical failure modes which had been previously documented in experimental studies include use of core shear, face-sheet wrinkling, face/core debonding, core crushing, and delamination [4]–[6]. As an illustration, Wang et al. [4] conducted three-point bending experiments with natural and synthetic fiber-reinforced composite honeycomb panels and those found to have the

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[*] Corresponding author: ashok.magar@gmail.com

most common failure modes were delamination and debonding. Deng et al. [5] analyzed carbon-fiber reinforced corrugated sandwich beam and came up with failure-mode maps that are associated with load, deflection, and core geometry. Wang et al. [6] also illustrated that face-sheet thickness and core density are very important factors that determine bending response, energy absorption, delamination behavior, etc. A number of studies have suggested interface-toughening to reduce delamination. Other methods have also led to greater interfacial bonding results, including stitching, Z-pinning, and placing fibers between the face sheet and core have also improved bonding, although some of these methods can damage face sheets or they are hard to apply to metallic cores [7]–[9]. Shigang et al. [7] showed that interface toughness is increased because of stitching after the tension and bending test. Hayta et al. [9] found that stitched sandwich structures had higher the resistance to damages than the unstitched ones. In a more recent approach, scientists have been interested in fiber-bridging methods with short aramid/Kevlar fibres and carbon belt with the view of reinforcing the interface. In aluminum-foam core sandwiches, Wang et al., [10], Sun et al.[11] showed that short Kevlar fibre tissues enhance bond strength, and the length of the fibre and isal density are parameters of influence. However, in their case, honeycomb cores were not improving much since the area of bonding between the sides is less. Kolopp et al. [12] also experimentally compared perforated and stitched core sandwich panels and found a better mechanical performance to solid-core ones. Yu et al. [13] also examined aramid-fiber tissues and carbon belts in three-point bending and found that the processes of crack isolation and fiber bridging were used to slow delamination. More recent work (20192023) has and is extending these findings based on current high-frontier experiments. Chen et al. [14] reinforced carbon-nanotube films in CFRP honeycomb sandwiches and obtained an improvement of 2030 per cent in interfaces toughness. Li et al. [15] experimented on hybrid fiber-belt toughened panels being subjected to dynamic bending and found that energy absorption was significantly enhanced in comparison to untoughened structures. Daud et al. [16] studied the load rate factor and identified that the increased the loading rate the slower the crack initiation; however, the faster the failure becomes catastrophic. Raj et al. [17], in their paper, examined aluminum hybrid composite foam-core sandwiches using Kevlar and carbon-fiber face sheets and found a significant flexural rigidity, strength, and energy absorption with respect to bare foam, which understanding the crashworthiness of such hybrid designs.

In spite of these developments, very little research has been carried out to establish the effect of short-fiber belt stitching on interface behavior of honeycomb-core sandwich panels. Consequently, the current study will improve the interfacial bond strength of the carbon fiber face sheet reinforced composite (CFRC) sandwich structures having aluminum honeycomb cores. This is done by adding the short Kevlar fiber tissues at the interfaces and experimentally comparing their performance with the untoughened specimens. To investigate flexural behavior, find out the mechanisms of failures, and check the efficiency of the proposed toughening method, the three-point bending tests will be performed.

Musculoskeletal conditions are characterized by limitations in mobility and reducing people’s ability to walk and work. A study of the Global Burden of Diseases, conducted by the Institute for Health Metrics and Evaluation (IHME) in 2021, states that approximately 1.71 billion people are affected by musculoskeletal disorders, making them the largest contributor to disabilities in the world [1]. Although the occurrence of these conditions varies with age, people of all age groups are being affected by them.

2 Experiments

2.1 Material

This paper analyzes flexural behaviour of carbon-fiber composite sandwich plates that use an aluminium honeycom core. The face sheets were made with carbon woven cloth and carbon fiber face sheets and the aluminium honeycomb core were both purchased by Composite Tomorrow Pvt. Ltd., Vadodara. Table 1 gives a summary of the mechanical properties of these constituent materials. The bonding adhesive to all the interface layers was an epoxy hardener system of a 10:3 ratio.

Table 1. Specification of carbon fiber face sheet and honeycomb core.

Components	Properties	Notations	Value
Face sheets (2x2 twill carbon)	Modulus of Elastisity	E_1	231 (GPa)
	Modulus of rigidity	G_{12}	90 (GPa)
	Poisson's ratio	ν	0.30
	Strength	σ_t	421 (GPa)
	Areal density	ρ_A	240 (gsm)
Aluminum grade of honeycomb core (AA3003)	Modulus of Elastisity	E_{Al}	69 (GPa)
	Poisson's ratio	ν_{al}	0.33
	Ultimate strength	σ_u	155 (MPa)
	Density	ρ	2680 (Kg/m^3)

Geometry of unit cell of honeycomb used in the present work is shown in the Fig. 1. The geometrical parameters majorly affect the structural response of the honeycomb shaped core.

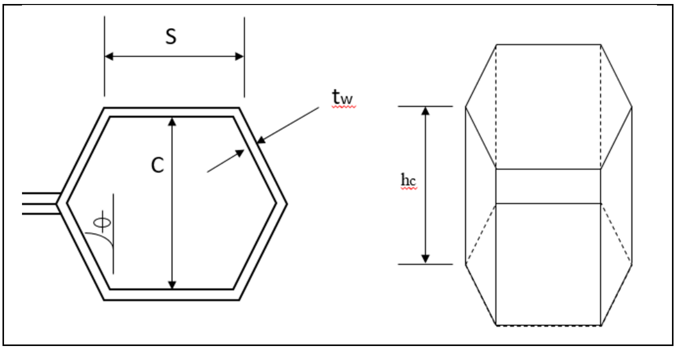


Fig. 1 Geometrical representation of honeycomb unit cell.

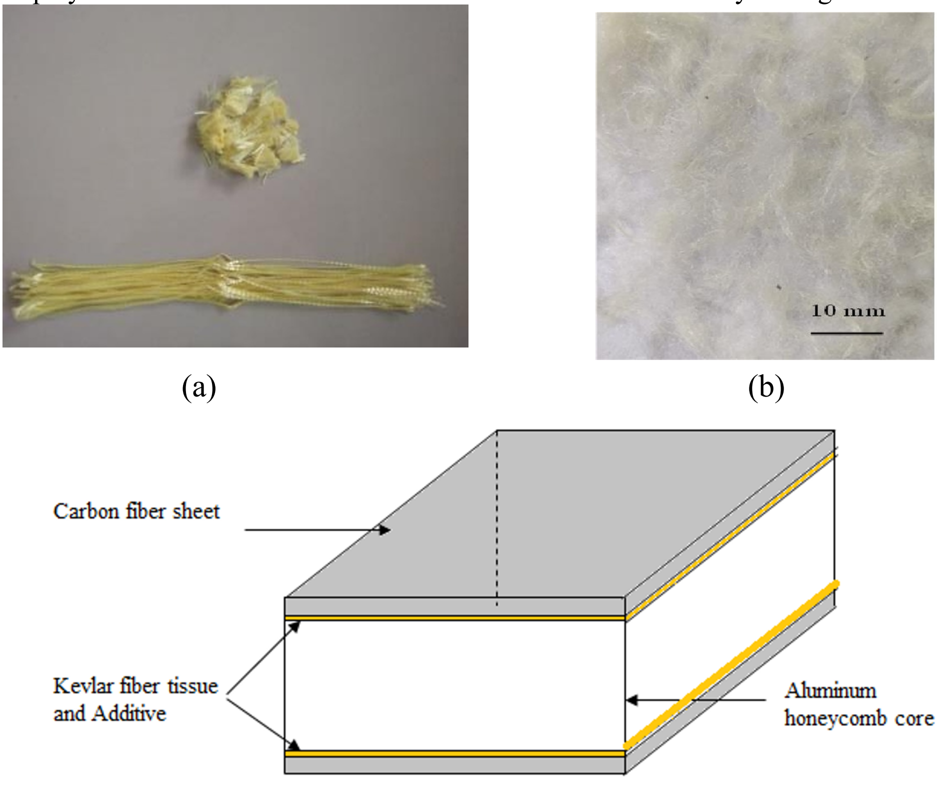
A Mechanical property of the honeycomb shape core depends on its various dimensional parameters shown in the Fig. 1. Table 2 presents the dimensional parameters of the hexagonal unit cell.

Table 2. Dimensional parameters of honeycomb unit cell.

Parameters	Notations	Size
Edge	s	4 mm
Cell size	c	6.93 mm
Cell strip thickness	t_w	0.07 mm
Height of cell	h_c	20 mm
Core angle	ϕ	30^0
Interior angle of cell	θ	120^0

2.2 Fabrication of Sandwich Plate

The Honeycomb core sandwich plates with carbon-fiber face sheets were made using the hand lay-up technique. The interfaces toughened due to incorporation of Kevlar fiber tissues and bonding of the face sheets with aluminum honeycomb core. To make the toughening material, Kevlar-49 fibers were first cut into short fibers of approximately 8 mm as was shown in Fig. 2(a). A blunt-blade grinder was used to transform these small fibers into a tissue form as observed in Fig. 2(b). Figure 2(c) represents the sequence of the composition of the fabricated sandwich plates. The interfacial toughening layer that was employed was in the form of Kevlar fiber tissue with an areal density of 12 gsm.

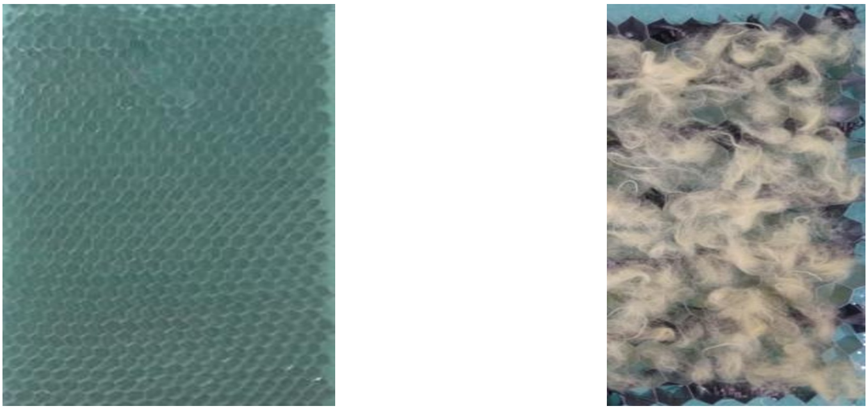


(a) (b)

(c)

Fig. 2 (a) Kevelar fiber, (b) tissues of Kevlar fiber, and (c) geometry of sandwich specimen

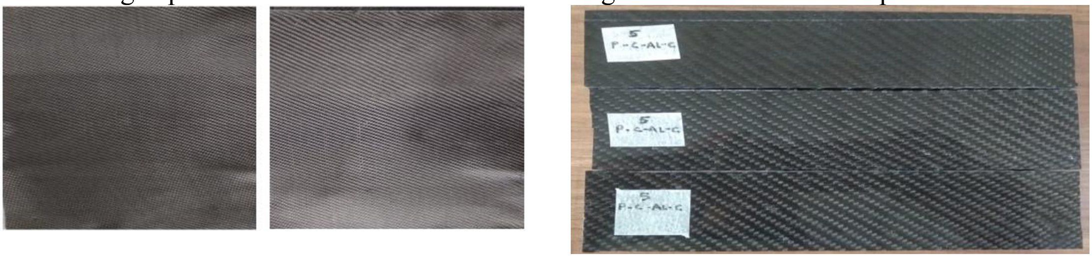
Interfacial toughening was added by placing two layers of short-fiber tissue in between the sheets of the face and the honeycomb core at each of the interfaces. The mix of epoxy-hardener has been used to bond all the interfaces as above. The outcome of this design, which incorporates Kevlar short-fiber tissues at both of the bonding interfaces to augment interface strength and crack-bridging, is technically referred to as the K-Sandwich in this paper.



(Plain Honeycomb Core) (Honeycomb Core with Kevlar interface)

Fig. 3 Core (a) without toughening, and (b) with interface layer of Kevlar tissue

Fig. 4 presents the carbon fiber face sheet along with the sandwich test specimens.



(a) (b)

Fig.4 (a) Face sheet of Carbon fiber, and (b) fabricated sandwich specimens.

3 Results and Discussion

3.1 Bending test of sandwich plate test specimen

Test specimen is fabricated as per ASTM C393 for three point bending test shown in the Fig.5. Dimension of the test specimens are 160 mm × 50 mm × 21 mm. Three pace of loading are considered as 5 mm/min (slow), 50 mm/min (medium), and 300 mm/min (fast) on the basis of literature survey.

The deformation–failure mode was defined as the point at which the mid-span transverse deflection reached one-third of the specimen length, or when the applied load decreased to 5% of its peak value during the test.

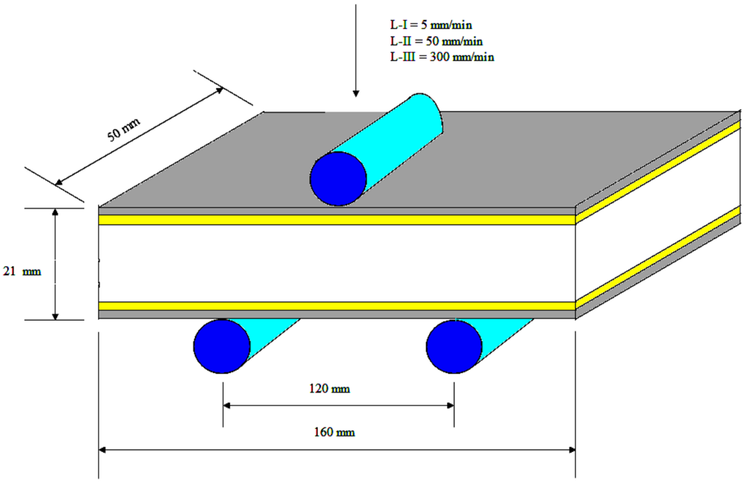
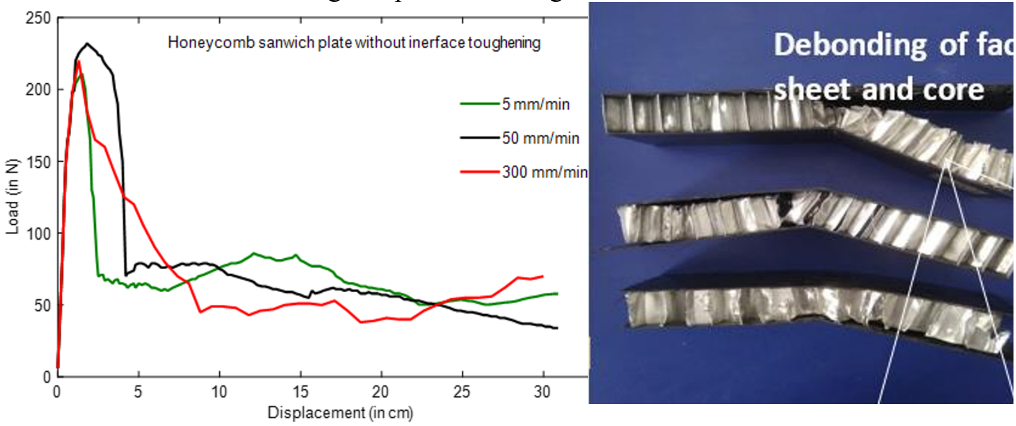


Fig. 5 Specimen geometry for 3-point bending test.

3.1.1 Load–displacement curves for the plain sandwich (P-sandwich) specimens.

Plain sandwich specimens (no interface toughening) were load tested at three-point bending at the three loading rates mentioned above. Three specimens were taken to provide repetition of each loading rate. Lower Fig. 6(a) illustrates the loaddeflection response of a typical plain specimen. During the initial loading phase, the linear trend between load and deflection is seen until a range of deflection (2-3mm) is reached. This tight coincidence of these early linear areas proves that the inflexibility of the sandwich construction is not a lot contingent upon the loading rate used.



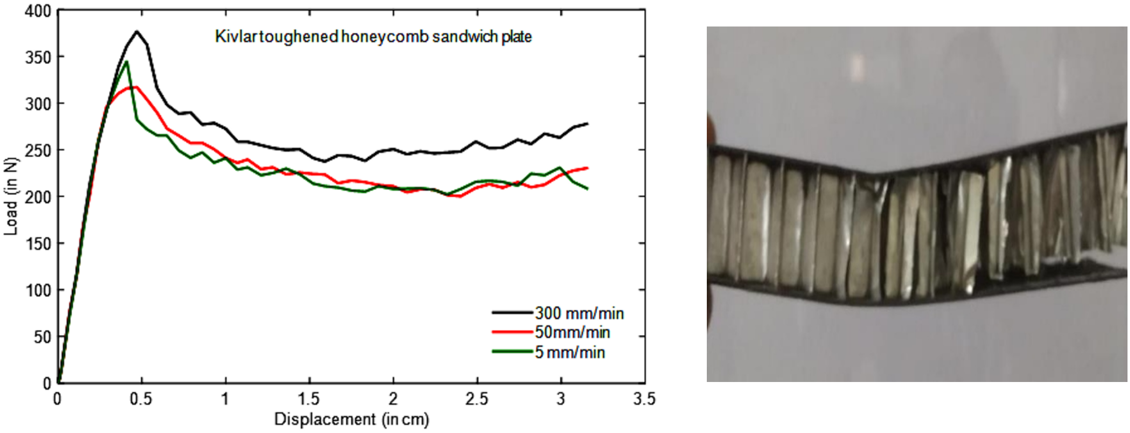
(a) (b)

Fig. 6 (a) Load–deflection response, and (b) failure behaviour of the sandwich plain sandwich specimen.

The specimens go through the elastic response phase after which they undergo plastic deformation phase where failure is initiated. The higher the loading rate, higher is the load capacity since shear failure of core takes place at the peak loading. The peak load is quite rate-dependent with maximum value at the highest loading rate and minimum at the slowest rate. The load decreases after the core shear failure and partial damage of the face sheet, but then, it levels off due to further deflection of the approximately 30 mm, and the curves become more or less parallel to the axis of displacement. Final failure occurs when honeycomb core and face sheets crack causing a total loss of flexural stiffness. The failure behaviour of the P-Sandwich specimen depicted in Fig. 6(b) comprises of explicit debonding between the face sheets and the core, as well as localised shear deformation of the honeycomb cells caused by bending of the face sheet.

3.1.2 *Interface toughening with Kevlar short tissues*

The effect of loading rate on flexural behaviour of Kevlar-toughened sandwich specimens is as shown in Fig. 7(a). The findings show that the changes in loading rate are insignificant at the first linear-elastic range that only exists within a limited deflection range. As soon as this elastic stage is reached, the specimens go into their peak load and the value of the peak is more pronounced with increased loading rates. Global crushing of the honeycomb core takes place upon reaching peak load leading to sudden reduction of the load by approximately 40 percent. More than this, the load level off, and becomes almost constant, representing a deflection in the middle of about 3035 mm. The sandwich panels made of Kevlar-toughened material have a regular shear-dominated deformation behavior, this can be described by the fiber-bridging effect at the interface between the honeycomb core wall and the carbon face sheet. This reinforcement process improves the interfacial integrity and encourages global shear failure of the core, which is the most common form of deformation in the toughened specimens.



(a) (b)

Fig. 7 (a) Load–deflection response, and (b) Failure pattern of the Kevlar toughened Sandwich specimen.

3.1.3 *Effect of interface toughening*

Three point bending tests were used to measure the flexural response of CFR/honeycomb sandwich specimens at a medium loading rate of 50 mm/min. Fig. 8 demonstrates that the Kevlar-reinforced K-Sandwich had significantly better performance than the plain specimen. Interproven effectiveness of interface toughening Interface toughening at the interface gave a flexural resistance increase ranging from 36 percent to the same test conditions with the introduction of Kevlar short-fiber tissues at the interface proving the effectiveness of interface toughening in enhancing structural integrity. On the other hand, the plain sandwich specimen exhibited the smallest load-bearing capacity mainly because there was no interfacial reinforcement and thus it was prone to be debonded easily.

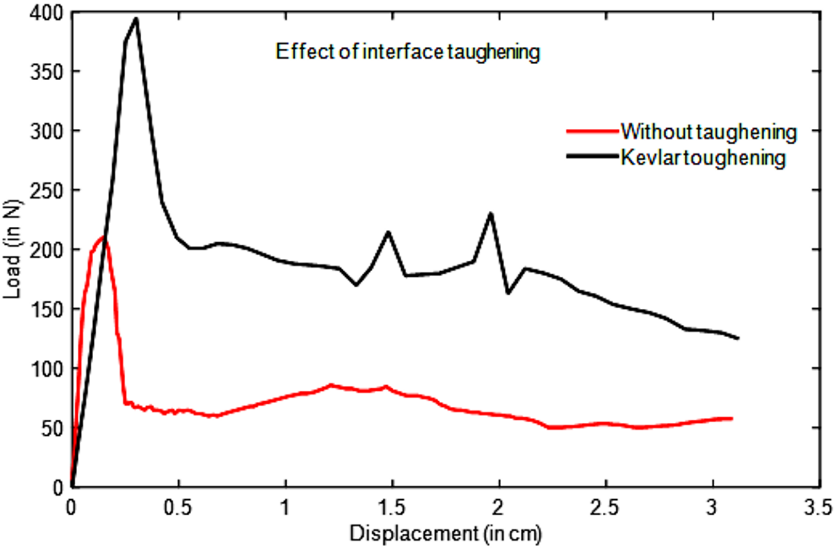


Fig.8 Effect of interface toughening at 50 mm/min loading pace.

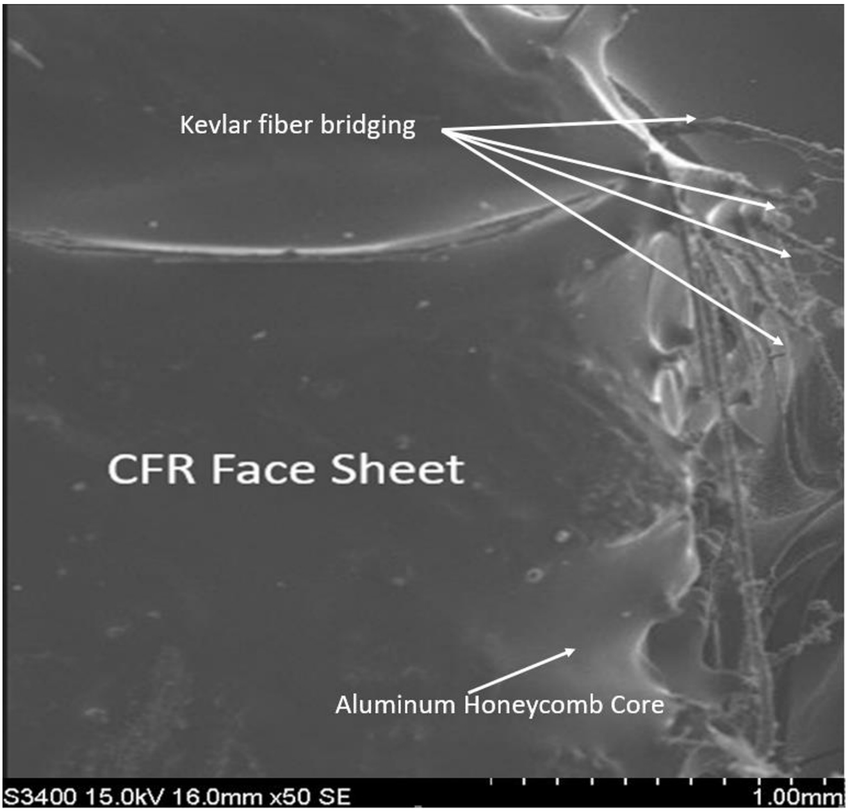


Fig. 9 SEM observations of the fracture mechanisms in Kevlar-modified sandwich panels.

Fig. 9 shows the load displacement characteristics of honeycomb sandwich samples with and without Kevlar interface toughening and the resultant SEM micrograph of the

Kevlar-reinforced interface. In the SEM image, it is evident that there are Kevlar short fibers between the interface face sheet of CFR and the honeycore, which increase the interfacial adhesion. Such fiber-bridging mechanism is an effective method of slowing down the delamination and fiber pull-out, and the sandwich panels can be subjected to high loads. The load-displacement curves also indicate that the Kevlar reinforced specimen have much better peak loads (about 41 per cent higher) and energy absorption than the untoughened specimen. Conversely, the untoughened samples experience premature interface debonding thus achieving low load bearing capacity and energy absorption. Hardened interface enhances the spread of stresses, and favors failure modes on a global scale, including shear and core crushing, as opposed to localized delamination, and enhances the overall structural performance at flexural loading.

The K-sandwich, which involved the addition of Kevlar short-fiber tissues to a sandwich panel, showed a startling increase in performance at almost no increase in weight, only 0.192 g. This minor addition causes rise in the peak load by 48 percent and the rise in energy absorption by 35 percent over a conventional panel. The slight improvement in the areal density of the panel was a direct factor towards a general increase in the specific strength.

In addition, the K-sandwich had a more consistent load-deflection behavior at the plastic region. This is because it is very stable due to the constant fiber bridging that forms a heavy bond between the face sheets of the panel and the walls of the honeycomb core. The results clearly show how a light and easy to implement modification can dramatically enhance the mechanical characteristics of a material without interfering with its weight-efficiency.

4 Conclusion

Three-point bending experiments were performed to evaluate the flexural behavior of plain and Kevlar-reinforced (K-Sandwich) CFR/honeycomb sandwich specimens. The study examined the influence of loading rate, interfacial toughening, and face-sheet thickness on the structural response. The findings confirm that interface toughening significantly improves the overall mechanical performance of the sandwich plates, although a slight reduction in specific properties occurs due to the associated increase in mass. Therefore, achieving an optimum balance between strength enhancement and weight gain is essential for practical design. The major conclusions are summarized below:

- Plain sandwich specimens predominantly fail through face-sheet wrinkling, core crushing, and debonding at moderate to high loading rates. Their peak load and energy absorption levels are consistently lower than those of the toughened specimens.
- Kevlar-reinforced specimens show no evidence of face-sheet/core debonding. This improved integrity results from the fiber-bridging action of short Kevlar fibers, which impede crack growth and suppress delamination. The presence of carbon-fiber belts further enlarges the effective bonding area, thereby reducing debonding tendencies.
- Increasing the face-sheet thickness leads to higher peak load capacity but shortens the linear-elastic deformation range.
- Kevlar-reinforced specimens exhibit a more stable plastic deformation response, whereas carbon-belt-toughened specimens show noticeable load

fluctuations within the plastic region.

- K-Sandwich specimens experience only a marginal weight increase (0.192 g) while achieving approximately 48% higher peak load and 35% greater energy immersion compared to sandwich plate without interface toughening.

5 Future Scope

Future research can be conducted to examine the effect of various toughening materials e.g., aramid, basalt or hybrid short fibres to find out which interface-bridging method to honeycomb sandwich is more efficient. The influence of the length of Kevlar fiber, areal density, and tissue architecture on interfacial toughness can be investigated to maximize the ratio of strength increase to the increase in weight. Dynamic and impact-loading experiments (low-velocity impact, high-strain-rate bending, blast loading) are to be conducted in order to investigate the relevance of the toughening mechanisms under quasi-static loading to extreme conditions.

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