

Chapter 6. Indentation Damage Mechanics of FA Reinforced PU Foam Core Sandwich Composites

The assessment and scientific interpretation of the findings are carried out in accordance with the domain of research on the damage behaviour of various material configurations. The physical properties and mechanical properties like density, elastic modulus, yield strength of the face sheets and PUF core are already mentioned in previous chapters to refer these properties and predicting its response under indentation. The indentation resistance characteristics are elaborated in detail for different specimens. This study focuses on the sandwich structure's responses while considering the effect of GFRP and CFRP face sheets under quasi-static indentation. Fly ash loaded PUF core sandwich composites are investigated comprehensively. This study also investigates the response of sandwich composite with the change in nose profile geometry.

6.1. Indentation Response of Sandwich Composites

The sandwich composites are composed of two components: face sheets and a core. The properties of the sandwich components have been evaluated to understand and predict the response of sandwich composite under quasi-static indentation. The density of the face sheet and foam core has been tabulated in section 4.1.1. The mechanical properties and deformation characteristics of the components has been evaluated and discussed in section 4.2 and 5.1 which gives us the solid foundation to investigate the indentation response of the sandwich composites.

This work focuses primarily on how the shape of the indenter's nose tip affects the indentation behaviour of neat PUF GFRP/CFRP sandwich composites and, more critically, how nose tip shape affects deformation behaviour of FA-PUF GFRP/CFRP sandwich composites. A few scientific studies on the latter section are available. The effect of

reinforcement on the indentation resistance offered by indenters with various nose tip shapes is examined in this study. For various combinations, the impact of reinforcement with regard to each indenter nose tip geometry has been assessed. The study is conducted in the following order: first, the effect of the flat-circular, hemispherical and conical indenter on a neat PUF sandwich composite is investigated. The ASTM specimens are fabricated from a single, precisely constructed neat PUF GFRP/CFRP sandwich panel, and the process is repeated for GFRP/CFRP sandwich composites with 5%, 10%, 15%, and 20% fly ash inclusion to PUF core.

In sandwich composites, the face sheet is clubbed to a low-density core material for enhancing its out-of-plane load carrying capabilities. Because the face sheet alone is susceptible to out-of-plane loading, strategically, the deformation behaviour of foam core under indentation has already been investigated in chapter 5. Now, the quasi-static indentation test has been performed on sandwich panels. This test is conducted to study the indentation resistance of the neat and FA reinforced foam core. As shown in figure 6.1 and 6.2, the effect of geometry on indentation resistance is evaluated using three different types of indenter nose shapes. The cut cross-sections of the indented neat PUF GFRP and CFRP sandwich specimen are also shown for better understanding of the damage/deformation incurred by flat-circular, hemispherical and conical indenter.

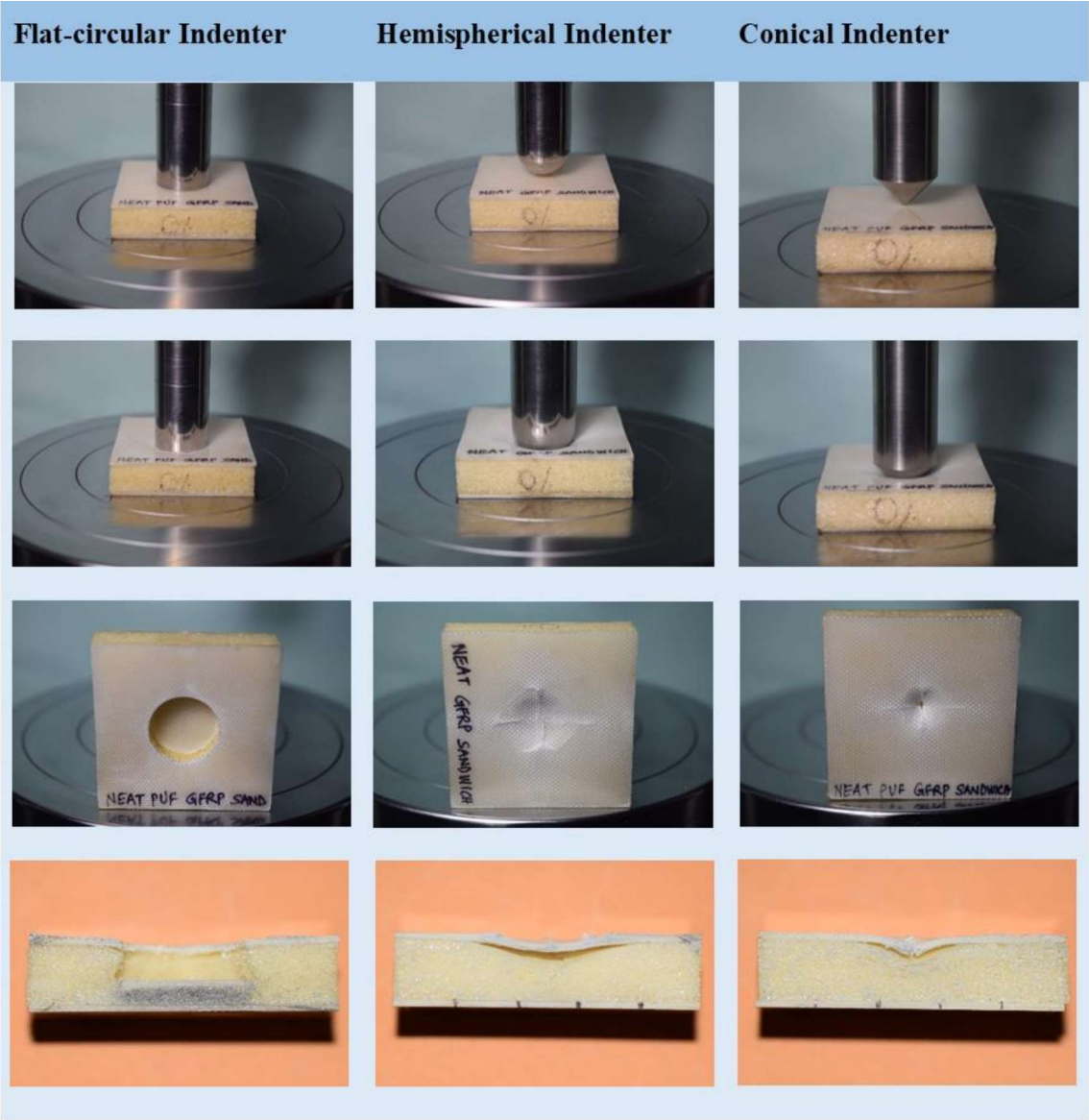


Figure 6.1 Experimental setup and deformation incurred on Neat PUF GFRP by the flat-circular, hemispherical and conical indenter.

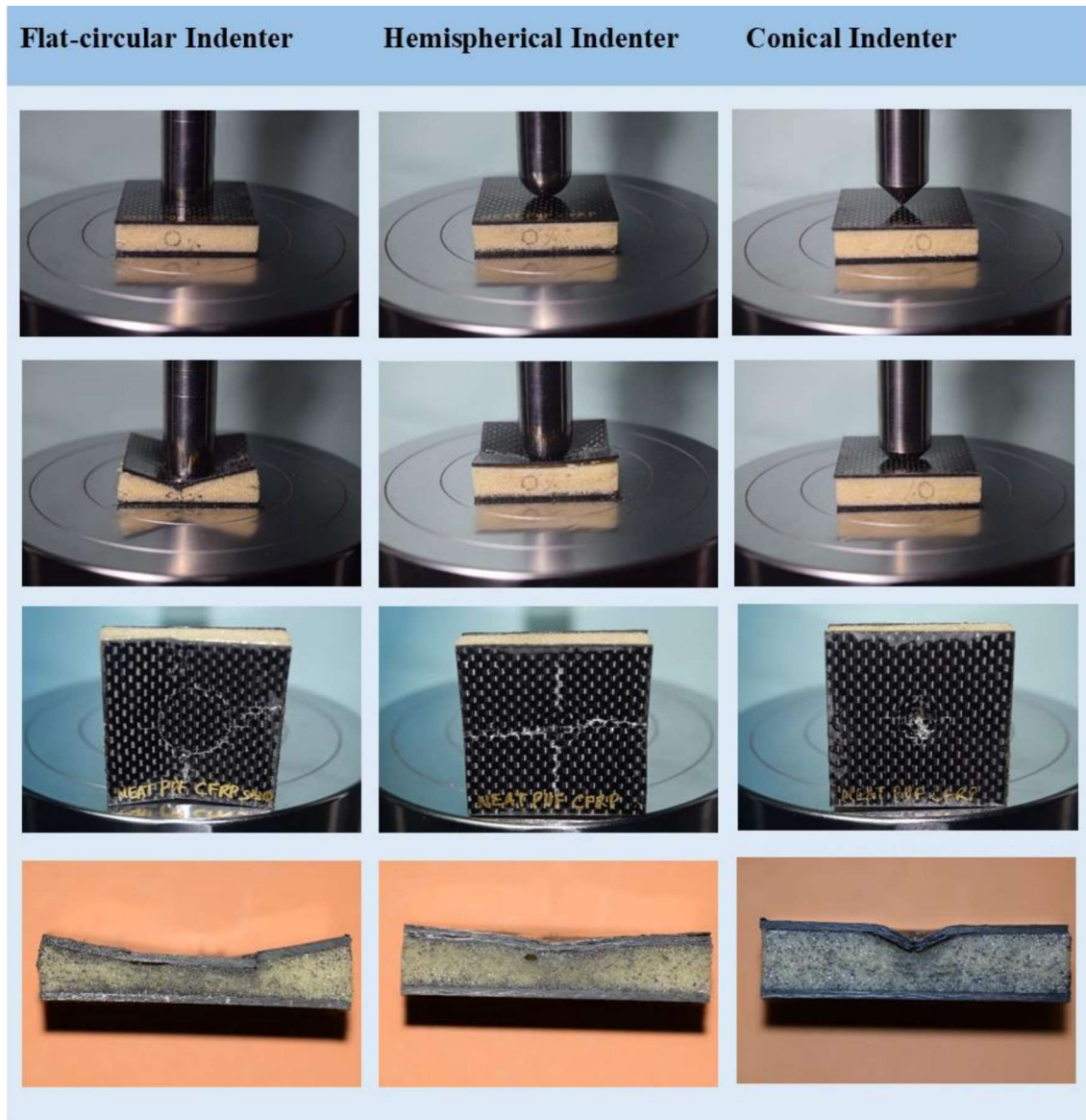


Figure 6.2 Experimental setup and deformation incurred on Neat PUF CFRP by the flat-circular, hemispherical and conical indenter.

It's critical to comprehend how the indentation develops in the foam core sandwich composite and leads to a dent. The resisting force is seen to increase with the indentation depth during experimentation. However, the pattern of the force variation with indentation is mainly reliant on the geometry of the indenter tip and face sheet of the sandwich composite. The load vs indentation curve characteristics is dependent not just on the indenter's nose tip geometry or face sheet but also controlled by the deformation behaviour

of the reinforced PUF core. Therefore, it is necessary to study the effect of reinforcement on the deformation behavior under different nose shape indentation, which also contributes to the indentation resistance behavior.

6.1.1. Effect of Indenter's Nose Profile Geometry on Indentation Resistance of Neat PUF GFRP/CFRP Face Sheet Sandwich Composites.

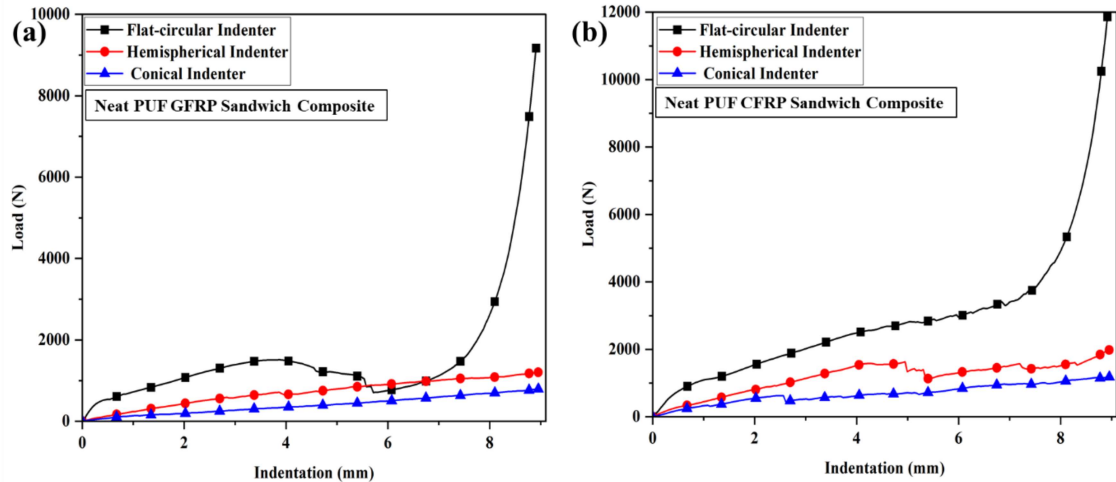


Figure 6.3 Load-Indentation behaviour of (a) GFRP and (b) CFRP sandwich composites under flat-circular, hemispherical and conical indenter nose profile geometry.

Figure 6.3 shows Load- Indentation curve, indentation response of neat PUF GFRP and CFRP sandwich panel using various indenters. Each indenter has a unique impact on sandwich structure. The variation in load reveals that how the geometry of the nose affects the interaction between force and indentation depth. The deformation behaviour of face sheet and closed-cell PUF affects the load variation with respect to indentation depth. From the Load-Indentation curve, it is clear that, initially elastic deformation at lower strains occurs until it reaches the crest and then the onset of plastic collapse and crushing of cells begins accompanied with the matrix cracking in upper face sheet. The rise in the load value in the plastic region is because of the stiff face sheet which compresses more PUF core coupled to it and not just the projected area beneath the indenter. It was observed during the indentation testing that the compression zone generated in the PUF core is getting larger with indentation

depth. This happened because of the influence of stiff face sheet which is bonded with the core. Subsequently, there is a drop in load value with indentation depth. This load drop initiates with the matrix cracking and delamination which further leads to fibre breakage at the contact site of the flat circular indenter. This type of failure is known as shear plugging. Later, indenter punctures the foam core beneath the indenter. After the face sheet and cell wall ruptures along the circular edges, the cylindrical surface area of the indenter is exposed to the foam, may cause friction opposite to the indentation direction. This might also have contributed to the rise in indentation resistance. Further, the load increases rapidly, indicating the densification of the closed-cell PUF backed by rigid support. The indentation resistance offered by the neat PUF sandwich composite to the hemispherical indenter lies in between the flat-circular and conical indenter. Initially, it shows an elastic increment with load, but the gradient of the curve is lower than the flat-circular indenter but higher than the conical indenter. For the same target neat PUF sandwich panel, the indentation response shows that the value of resistive force changes with the nose geometry.

In case of hemispherical indenter, in the beginning the face sheet experiences high contact force exerted at the point of contact between the face sheet and indenter nose tip. Since, the face sheet is quite rigid in comparison to the foam core, hence deforms locally. The local deformation of the face sheet compresses the foam core under the contact area. Consequently, the load carrying capacity of the sandwich panel is very low with respect to the flat-circular indenter. After hitting the first peak the elastic buckling and plastic crushing of cellular structure of core occurs accompanied with the matrix cracking. Matrix cracking leads to the delamination in the face sheet. While the load carrying capacity increases with the indentation depth as indenter advances. This increment in load carrying capacity is due to the increment in the contact area between the indenter tip and laminated face sheet of the sandwich panel. From the Load-Indentation curve one can notice the drop in load. This load

drop indicates the delamination and fibre-breakage. Here, the hemispherical indenter punctures the face sheet of the sandwich panel. Thereafter the load increases with gradual increment in the contact area of indenter to sandwich panel where it crushes the foam core and propagate the puncture made in the face sheet. There is no significant increment in the load, which shows densification just started in case of hemispherical indenter.

Contrastingly, for the case with a conical indenter, the curve shows that the indentation resistance value is the least for the conical indenter. The low value of indentation load is because of the sharp tip of the conical indenter. It tears the face sheet of sandwich panel at the point of contact and travels through the foam core. Little resistance under the indenter tip initially makes it easy to puncture through the laminated face sheet and supports the low load value in the early stage of the load-indentation curve. It shows conical tip predominantly confronted higher contact stresses offered by the neat PUF core sandwich panel. However, as the indenter progresses into the foam core, more surface area gets in contact with the neat PUF sandwich panel, boosting indentation resistance. Face sheet tearing, crushing and shear resistance are significant determinants to study indentation under conical nose tip geometry. Tearing of the face sheet occurs, followed by the face sheet puncture. Crushing resistance is provided by the region surrounding the tip of the indenter. It increases with indentation depth, whereas shear resistance is induced by friction at the conical indenter-foam core interface. Consequently, the area of contact with the foam core increases corresponding to the indentation depth, increasing indentation resistance. The curve does not capture the densification phenomena because the densification zone is relatively small, just under the indenter tip. Therefore, its contribution to the nature of the curve is trivial.

By observing the figure 6.3 (a) and (b), surely it can be concluded that the indenter's geometry certainly has great impact on the load carrying capacity of the sandwich

composites. In case of neat PUF core GFRP and CFRP sandwich composites, the load carrying capacity or the indentation resistance is highest for the flat circular indenter while lower indentation resistance has been noticed for hemispherical indenter nose profile geometry. But, the least resistance to indentation is noticed for conical indenter.

6.1.2. Effect of Face Sheet Material on Indentation Resistance of Sandwich Composites with respect to each Indenter’s Nose Profile Geometry.

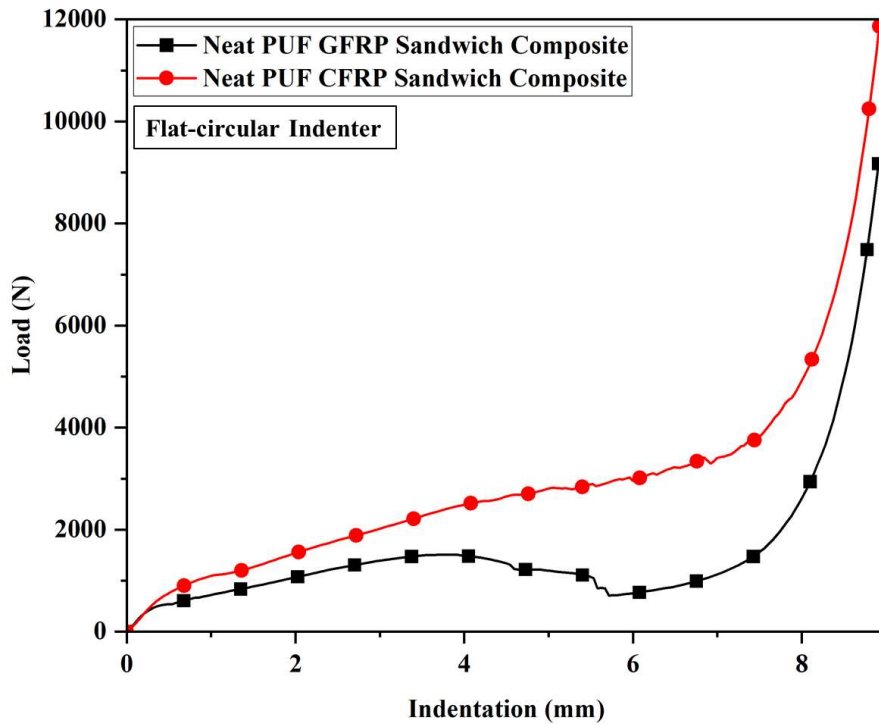


Figure 6.4 Load-Indentation curve behavior of Neat PUF GFRP and CFRP sandwich panel under flat-circular indenter.

From figure 6.4 it has been observed that the response of the CFRP sandwich composite is better than the GFRP sandwich composite under flat-circular indenter. This improvement is due to the superior stiffness of the CFRP laminated face sheet in comparison to GFRP laminated face sheet. The stiff CFRP face sheet enables it to transfer indentation load to larger part of the PUF. The load transfer is not limited to the projected area under the indenter, but goes beyond it. Therefore, the load carrying capacity of neat PUF CFRP

sandwich composite is greater than the neat PUF GFRP sandwich composite. This conforms the CFRP is having higher first peak, and slope after first is also higher in the plastic crushing region. Then the slope of the CFRP is declined after 5 mm indentation depth. The declination in the slope value is because of matrix cracking, delamination, fiber breakage and shear plugging. But the indenter could not fully disintegrate the punctured area from the face sheet. But, a larger drop in neat PUF GFRP has been noticed after 4 mm of the indentation depth. The matrix cracking and delamination start at 4 mm indentation depth which leads fibre breakage which stimulate the shear plugging. Sudden drop after 5.5 mm indentation depth depicts the separation of puncture plug from the face sheet. And after that the densification is observed with increment in the load value in both neat CFRP and GFRP sandwich composites.

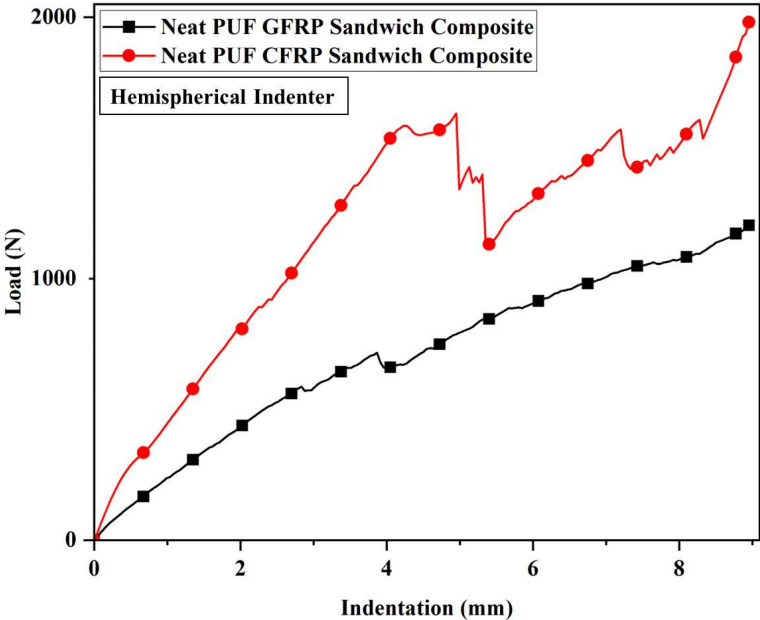


Figure 6.5 Load-Indentation curve behavior of Neat PUF GFRP and CFRP sandwich panel under hemispherical indenter.

Figure 6.5 also depicts the superior performance of the CFRP sandwich composite performs better than the GFRP sandwich composites. The reason for higher indentation resistance under hemispherical indenter is same as that of the flat-circular indenter which is higher

stiffness of CFRP laminated face sheet. Contact area for hemispherical indenter is very low in comparison to the flat circular indenter. Small aberration in slope near 3 mm indentation depth depicts the matrix cracking and initiation of the delamination due to shear stresses generated in the upper face sheet, which later on leads to the fiber breakage at the contact site of the indenter. In case of CFRP sandwich composite this happens near 5 mm of indentation depth while GFRP sandwich composite experiences this near 4 mm. Due to higher CFRP face sheet stiffness sudden fall in load has been noticed while GFRP face sheet with lower stiffness does not show much load drop. After that hemispherical indenter increases the punctured surface area with increment in indentation depth. CFRP face sheet shows higher resistance to the puncture resistance than the GFRP face sheet.

Figure 6.6 again depicts the superior indentation performance of the neat PUF CFRP sandwich composites over the neat PUF GFRP sandwich composites. But the difference engendered by the conical indenter is due to even higher contact stresses which tries to pierce the upper face sheet. The resistance against piercing is higher for CFRP laminated face sheet than the GFRP face sheet. After puncturing through the upper face sheet indenter travel through the sandwich composite. The resistance offered is principally depends on the fiber breakage of the upper face sheet which is created by the indenter travel perpendicular to the sandwich composite. The indenter travel tears the face sheet and while compresses the foam core beneath the face sheet. The tearing resistance of CFRP face sheet is higher therefore higher aberration can be noticed after piercing through the face sheet. While GFRP laminate face sheet curve embodies low tearing resistance. Densification under conical indenter is trivial.

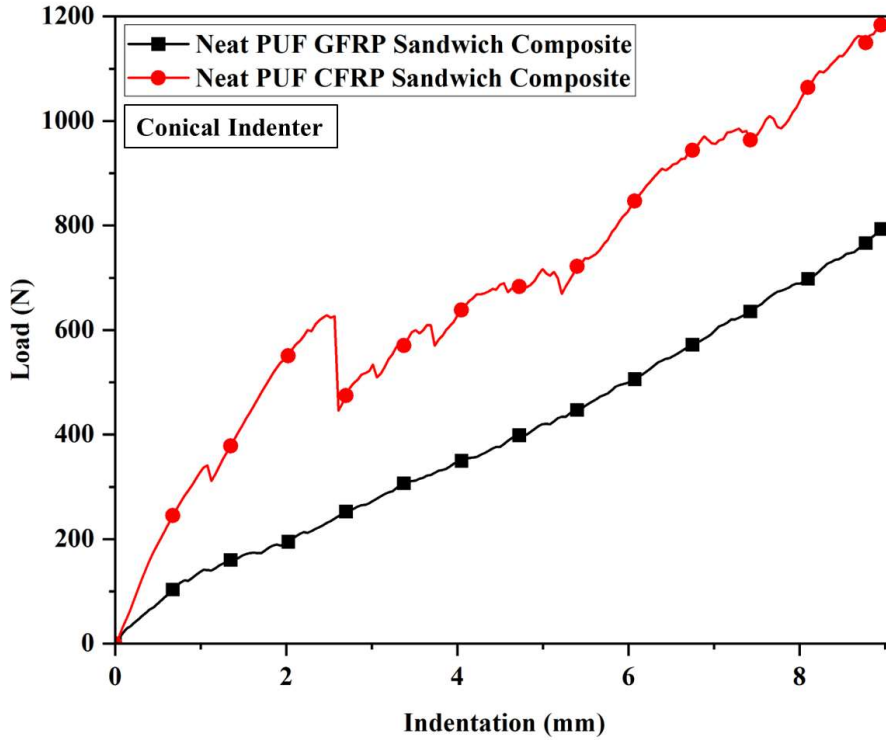


Figure 6.6 Load-Indentation curve behavior of Neat PUF GFRP and CFRP sandwich panel under conical indenter.

6.1.3. Effect of FA Reinforcement on Indentation Resistance of PUF Core Sandwich Composites.

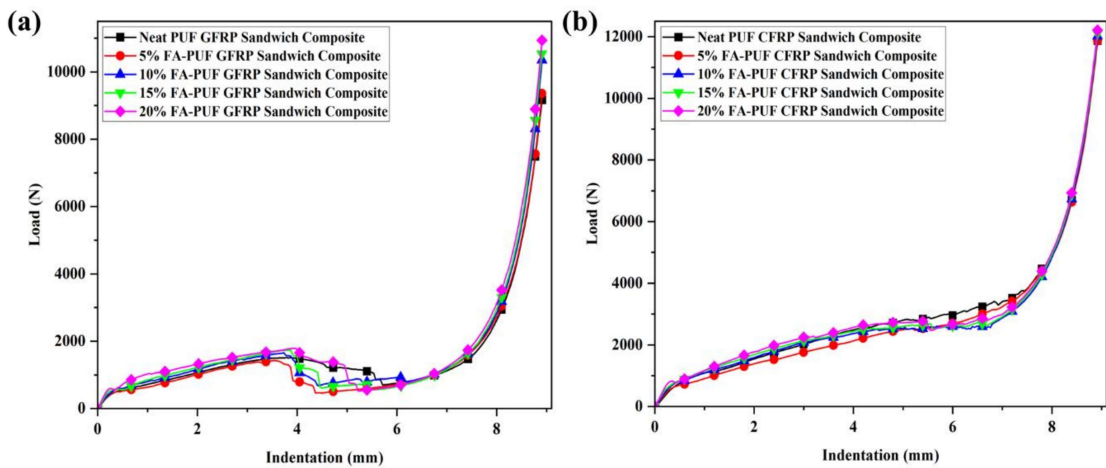


Figure 6.7 Load-Indentation curve of neat and reinforced FA-PUF core (a) GFRP and (b) CFRP sandwich composite under the flat-circular indenter.

The Load-Indentation curve for a neat and reinforced PUF core GFRP/CFRP sandwich composite under a flat-circular indenter is shown in figure 6.7. The neat and reinforced foam core GFRP/CFRP sandwich composite initially exhibits elastic behavior, followed by a prolonged plateau indicating elastic deformation of upper face sheet and plastic crushing of the closed cells. Finally, a surge in the load value is observed due to the densification of the foam core. The indentation sequence through the PUF core is similar to the compression curve. However, closer inspection reveals two peaks in the plateau region, unlike the compression curve. The first peak indicates the beginning of plastic core crushing beneath the face sheet. As the flat-circular indenter progresses further, more work is required to tear upper face sheet along the periphery of the flat-circular indenter. Hence, this rise in the load leads to the second peak. Then, the indenter tears the upper face sheet of sandwich composite along the line of contact. There is a loss in load value due to matrix cracking and fiber breakage, and the indenter punctures the upper face sheet. The rest of the deformation mechanism is well aligned with the indentation deformation mechanism of the bare foam core. Another point to notice from the graph is that when PUF is reinforced with FA particles, the time between the first and second peaks gets longer. With the incremental wt.% addition of FA to PUF, the PUF foam becomes more rigid and can carry more compressive stress, and hence the above behavior might have been observed.

With reference to figure 6.8, the sequence of the interaction of the hemispherical indenter to the GFRP and CFRP sandwich composite can be divided into three parts. The first part of the curve starts with elastic deformation of face sheet and core. While the slope proceeds to the plastic crushing of the foam core and elastic deformation of the face sheet continues. The second part of the curve, where the slope recedes, shows the interaction of the indenter's hemispherical profile to the sandwich panel, and the third part is the densification of the core which is not very pronounced in this case. In the second part, as the hemispherical indenter

travels against the face sheet of the sandwich composite the contact area with the indenter increases. The immersion and increase in the contact area of the indenter govern the deformation mechanism of the sandwich panel.

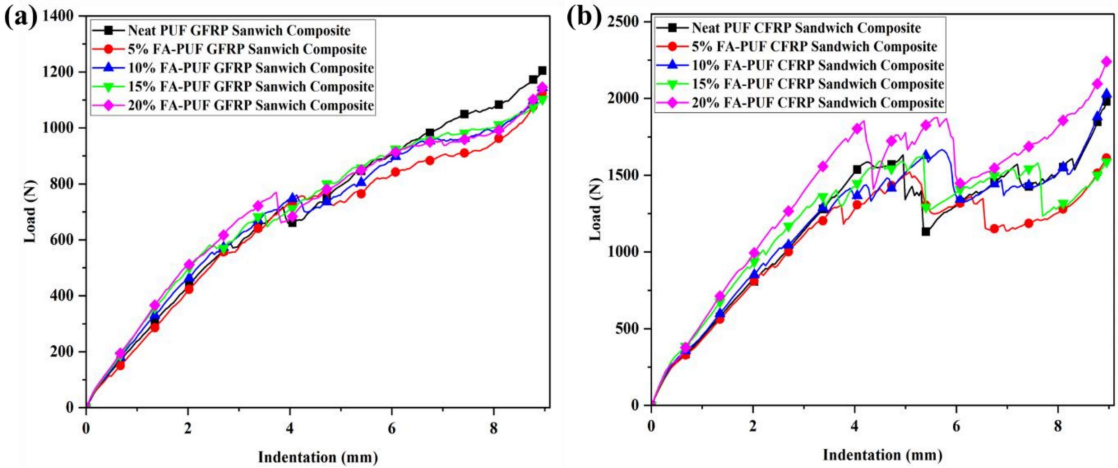


Figure 6.8 Load-Indentation curve of neat and reinforced FA-PUF core (a) GFRP and (b) CFRP sandwich composite under the hemispherical indenter.

After an initial constant slope, the recession in slope of the curve in the second part depicts the plastic crushing of the cellular structure accompanying the elastic deformation of the upper face sheet. However, the progressive new contact areas generated due to further penetration are governed by elastic deformation. Therefore, the plateau, which is evident in the case of indentation under a flat-circular indenter, is not the same for the hemispherical indenter. The plastic crushing of the core was accompanied by the elastic deformation of the core, which has resulted in a linear profile of the curve but with a lesser slope. After indenting GFRP and CFRP sandwich composite close to 4 mm depth, a drop in load indicates the matrix cracking, fiber damage that progresses to the shear plugging under the indenter projected area. The drop in the load is more significant in the reinforced PUF than the neat PUF indicating the increment in the rigidity of the PUF core with reinforcement. At the end of the second phase, shear plugging accomplished and consequently, the third phase of the

curve shows the surge in load value depicting the densification of the core against a rigid support.

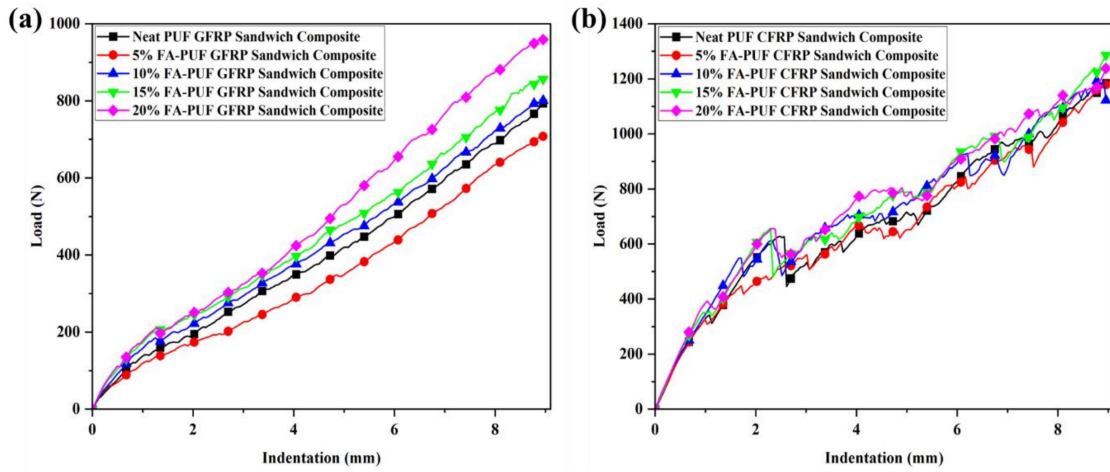


Figure 6.9 Load-Indentation curve of neat and reinforced FA-PUF core (a) GFRP and (b) CFRP sandwich composite under the conical indenter.

The characteristics of the conical indenter curve are significantly different from those of the other two curves, as shown in figure 6.9. Resistance to indentation offered by the PUF core is much less as reflected by the load values on ordinate with respect to the depth of penetration on the abscissa. It is pertinent to rethink the deformation sequence of the PUF core under a conical indenter. As the indenter begins to pierce the upper face sheet with its sharp nose tip, it starts penetrating through the upper face sheet from the beginning. But, as the indenter progresses by penetrating the upper face sheet and comes in contact with the PUF core, the resistance to indentation decreases. This happens because of the loss in integrity of the face sheet of the sandwich composite. Now, more surface area comes into contact with foam core because of the profile of the conical nose tip. The increment in resistance is due to the shear or friction force increment at contact site of upper face sheet and conical profile interface. In addition to the shear force, core crushing also contributes to the indentation resistance capability as evident from raise in the curve slope. So, the deformation sequence in the case of conical indenter starts with localised elastic deformation

of the sandwich composite prompts to puncture of upper face sheet followed by the crushing of PUF foam and shearing at the contact site with upper face sheet of sandwich composite. From the load-indentation curve in figure 6.9, it is evident that effect of reinforcement follows the same trends as that of previous indenter. Because here also the deformation of the sandwich composite largely depends on the foam core compression. But, in case of figure 6.9 (a) the elastic deformation of the less stiff GFRP face sheet sandwich composite with respect to stiffer CFRP sandwich composite shown in Fig. 6.9 (b). The drop in case of CFRP sandwich composite is higher than the GFRP sandwich composite. The load drop signifies the puncture through the upper face sheet. Further after the puncturing through the upper face sheet the deformation is based on the tearing of the upper face sheet and crushing of the foam core beneath the face sheet. Therefore, the reinforcement influence is same as that of flat-circular and hemispherical indenter. Higher the reinforcement higher will be the indenter resistance.

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