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Burning Behavior of Polyurethane foam Cored /E-Glass Reinforced/Vinylester Sandwich Composites: effect of core density and fibre architecture

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ABSTRACT

The present study is involved in investigating the flammability behavior of polyurethane foam cored E-glass reinforced vinylester sandwich composites. As fire is a major safety hazard for civil, commercial and transport systems, the objective of the work is to establish a complete assessment of properties pertaining to the heating and burning characteristics of these materials under fire. An attempt has been made to find the behavior of the wide range of sandwich specimens with varying core density and fibre architecture through its decomposition while at their burn. The composites burn primarily from the combustion of its resin material and burns in a manner similar to a charring material. The procedure involved in the test is to ignite the specimen with a pilot flame in horizontal and vertical positions. It is observed that, the burnt resin is forced out of the fiber pores, and burn pressure causes the material to swell over its original volume. Cracks are formed on the surface of core material and low density foam cores are found to be bending while burning. As the burning rate drops, extinction naturally occurs due to insufficient heating which is due to degasification of core.

Keywords: Sandwich composites, Fibre architecture, Flammability, Degassing, Fire extinction.

INTRODUCTION

Polymer sandwich composites find extensive applications in diversified fields like aerospace, automobile, infrastructure and marine due to their high strength to weight ratio, impact/damage resistance, fatigue resistance, thermal insulation and sound deadening properties [1]. A typical sandwich structure comprising of two stiff face sheets on either sides bonded by a flexible core, creates a synergistic structural configuration in which the face sheets provide bending stiffness and the core or foam, provides shear rigidity and buckling resistance. The use of sandwich composites in transportation and infrastructure building has become more prevalent in recent decades. Sandwich structures are being considered for these applications because of weight saving, lower construction cost and improved lifecycle cost. Along with the improvements to materials, construction methods and applications; comes an increased responsibility to ensure that systems are safe for their occupants and crew. Though sandwich composites are designed to have required structural response with respect to strength or deflections under normal operating conditions, their structural performance degrade rapidly at the elevated temperatures achieved during fire [2, 3]. Fire safety is one part of the overall safety concerns, but that is not well understood with regard to how composite materials behave under fire conditions. Most unprotected sandwich structures ignite after a short time when exposed to fire due to the high flammability of the polymer in the face sheets and polymeric foam core.

A large amount of research has been performed to characterize the fire properties of the composite materials, but only few works on sandwich composites. Polymer composites have long been weighed down by the problem of high flammability and poor fire resistance. This is a major problem encountered in composite materials used in applications such as aircraft cabins, ship decks, submarines, rail carriages etc., where they are vulnerable to fire [4-7]. Most composite materials ignite early when exposed to hot fire and large amount of heat, smoke and fumes are released. Mechanical properties of the composites are severely degraded by fire [8-12]. Fire studies have shown that mechanical properties of burnt region in composites are much lower than original properties mainly due to combustion of resin and thermal decomposition. Several studies on the fire behavior of composites have shown that softening of fibre reinforcement, thermal softening, creep and decomposition of matrix degrade the tensile properties, where as matrix softening and delamination cracking reduce the compressive strength properties [13-15].
Hence stringent regulations are enforced for the use of sandwich composites in aircrafts, ship, submarines and bridge structures for better fire performance. If the composite materials can be made to withstand fire ambiance without contributing significantly to the fire, then an acceptable level of safety can be achieved. In few cases, insulation can help to reduce the hazards associated with composite materials exposed to fire, but a thorough understanding about their burning behavior is essential before improvements are made. As compared to wood, some composites behave very well with regard to ignition and flame spread. These properties depend primarily on the type of resin used in the composite. The hazards associated with smoke and toxic products of burning plastics are also a major concern for passengers. Hence the objective of the present work is to study the effect of burning on different density PU foam cored sandwich composites. The materials were tested in ambient conditions. Material properties of sandwich composites such as ignitability in vertical and horizontal positions, weight loss and smoke formation under fire are discussed and reported.

MATERIALS AND METHODS

2.1 Materials

The sandwich specimens used in the present study comprise of four different grades of E-glass fabrics (supplied by Vetrotex /Saint Gobian, India) in vinyl ester resin supplied by Ecmas, Hyderabad and five varied densities of polyurethane foam (PUF) core supplied by polynate Foams Pvt. Ltd. Bangalore. The sandwich specimen face sheet is synthesized using 2% Cobalt Octate accelerator, Methyl Ether Ketone Peroxide (MEKP), Di Methyl Acetamide (DMA) and Vinyl ester. The fiber to resin volume ratio is maintained as 65:35. The samples are cured at room temperature for 24 hours followed by 70°C in oven for post curing. The sandwich specimen's specifications and various configurations used in the experiment are presented in Table 1.

Table 1: Sandwich Composites – Specifications

Sandwich Type	Resin	Fabric Type (E-Glass)	Core Material	Core Density(Kg/m^{3})
WR	Vinylester (3 mm facetted)	Woven Roving – 360 gsm	PU Foam (24 mm thickness)	100 - 300
CSM		Chopped Strand Mat-360 gsm		
SBM		Stitch Bond Mat -610 gsm		
CSM (S)		Chopped Strand Stitch Mat- 420 gsm		

2.2 Methods

Flammability Test

Flammability test of bare PU foams and PU foam cored sandwich specimens was done in accordance with ASTM D 3014 standards. The length, width and depth of specimen was 250x20x30 mm respectively. The test was conducted under both vertical and horizontal positions in accordance with UL94 VB and UL94 HB.

RESULTS AND DISCUSSION

Flammability test of bare PU foam core and PU foam cored sandwich composite specimens in vertical and horizontal positions are shown in Fig.1 and Fig.2 respectively.

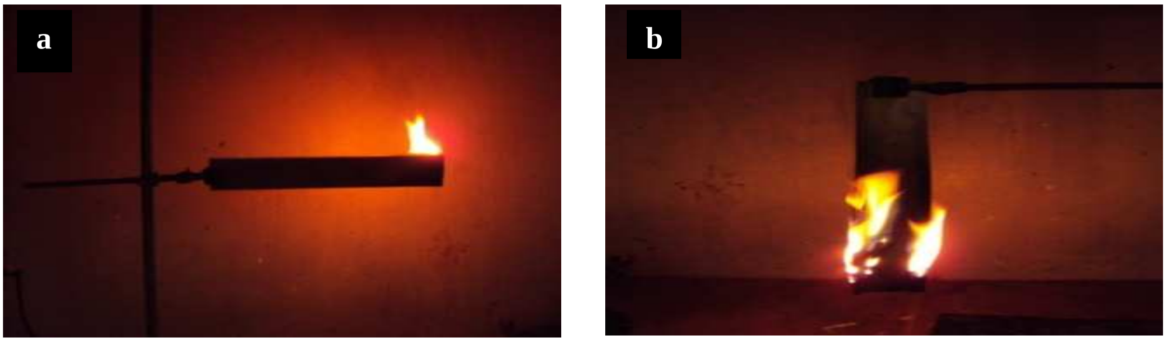

Fig. 1 (a) PU foam core under horizontal Testing (b) PU foam core under vertical Testing

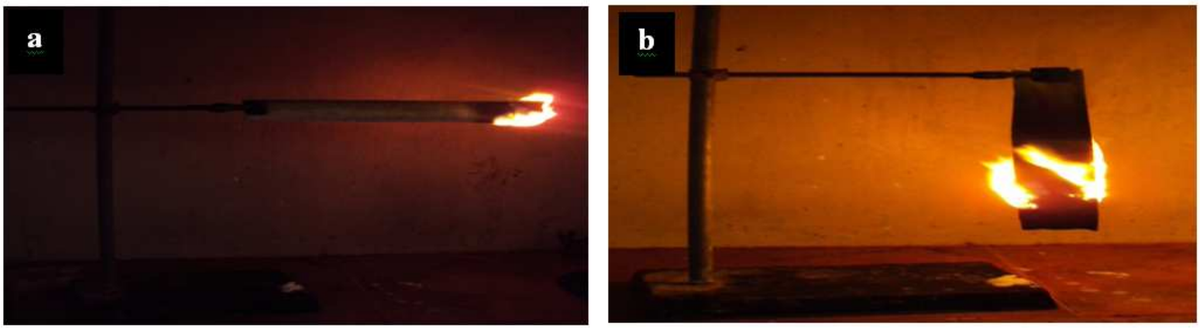

Fig. 2 (a) Sandwich under horizontal Testing (b) Sandwich under vertical Testing

For horizontal testing, the burner is ignited to produce 25.4 mm high blue flame. The specimens are exposed to 6.35 mm deep flame for 30 seconds without changing the position of the burner. Then the specimen is distanced from the burner. If the specimen burns to 25.4 mm mark before 30 seconds the flame is withdrawn. If the specimen continues to burn after the removal of flame, the time for flame front to travel from 25.4 mm mark to 100 mm from the free end is determined and the rate of burning is calculated. For vertical testing, a small 19.05 mm high blue flame is applied to the bottom of the specimen for 10 seconds, withdrawn and then reapplied for an additional 10 seconds. A layer of cotton is placed beneath the specimen to determine whether the dripping material ignites it during the test period. Through the flammability test the specimens are assessed for height of flame travel, time to extinguish and loss of weight under horizontal and vertical directions.

Time taken to ignite the specimens is given in Table 2.

Table 2: Time taken to ignite PU foam and sandwich composites

Specimens	Time taken to initiate flammability (Seconds)									
	Foam Density (Kg/m^3)									
	100		**150**		**200**		**250**		**300**	
	H	V	H	V	H	V	H	V	H	V
PU Foam	32	11	32	10	34	14	38	13	43	14
SBM	37	13	38	13	37	15	41	17	46	18
CSM	33	11	37	12	39	12	39	13	40	14
WR	34	12	36	13	43	13	44	15	46	17
CSM (S)	39	13	39	15	43	16	47	18	49	21

H- Horizontal Mode, V- Vertical Mode

There is not much difference in the ignition time for pure PU foam and sandwich specimens in the vertical and horizontal positions. Also ignition time does not vary significantly with the change in density of the core and the fibre architecture in the vertical position. Compared to vertical position, variation in the ignition time is more in the horizontal position. PU foam and sandwich composites did not show any dripping during burning. Therefore, PU foam cored sandwich specimens may not catch fire in the vicinity of other flammable structures.

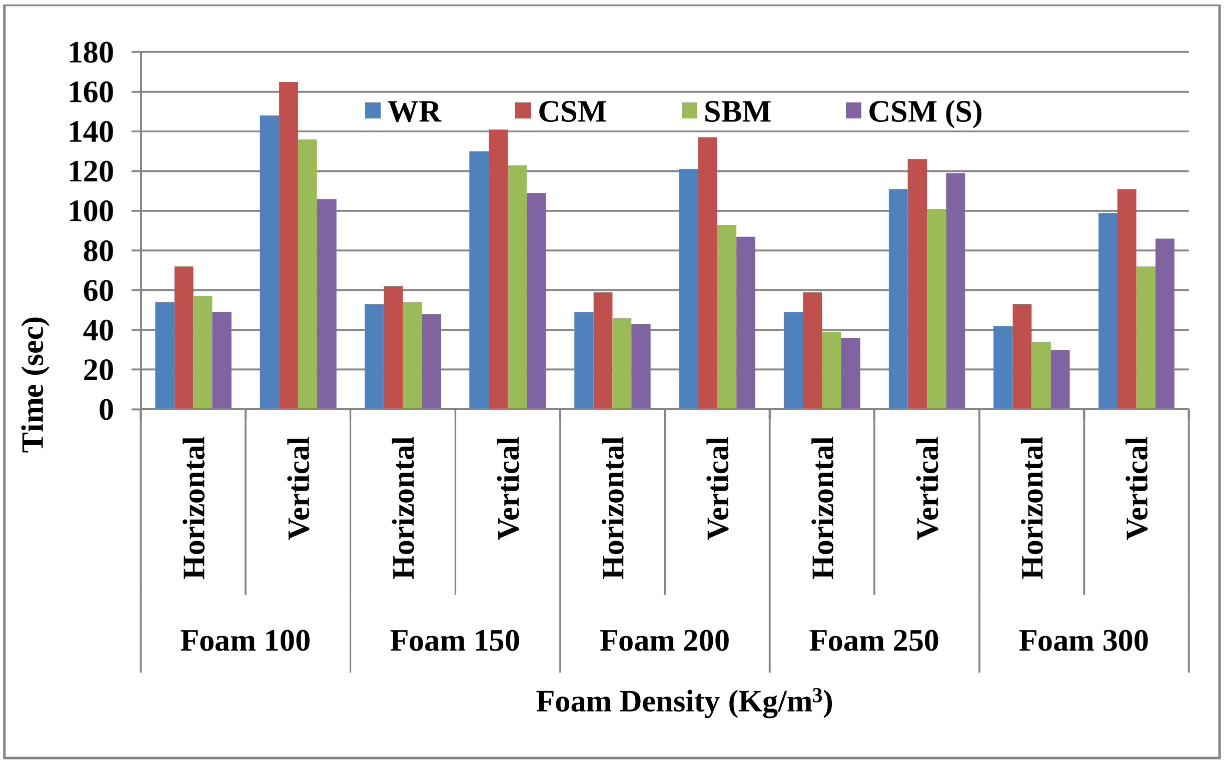

Fig. 3 Vertical and horizontal flame extinguishing time

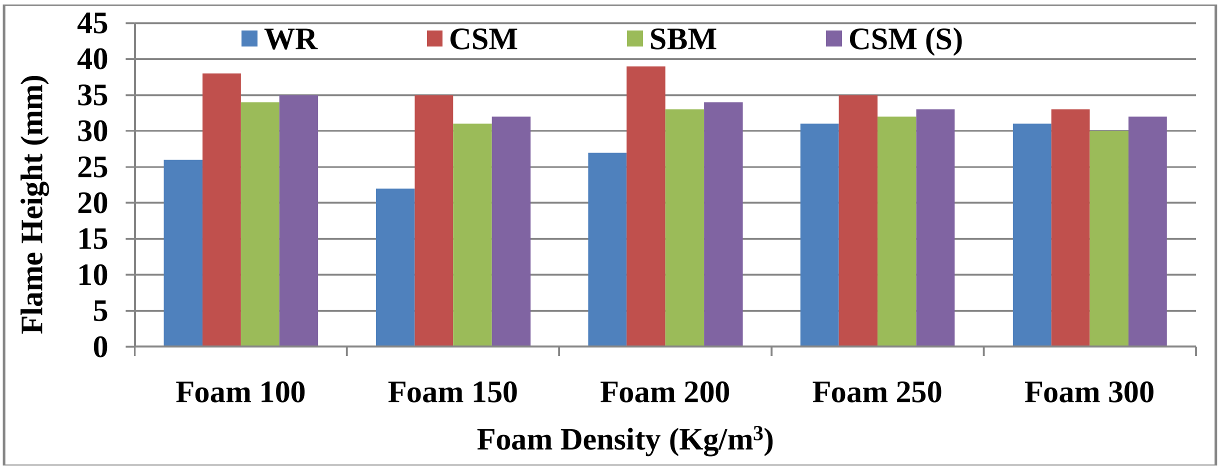

Fig. 4 Flame height V/s foam density in horizontal mode

Vertical and horizontal flame extinguishing time for various sandwich specimens is given in Fig. 3. It is evident from the Fig. 3 that, sandwich composites extinguish slowly in vertical rather than in the horizontal position. Time to extinguish is found to be maximum in the case of CSM sandwich composite and minimum in SBM and CSM (S) sandwich composites. The fire extinction in horizontal mode of testing is faster than in the vertical mode. In horizontal mode, the specimens failed to reach the opposite end (complete burning not possible) but in case of vertical mode the specimens were completely burnt. It is also noted that CSM sandwich composites have more flame height and minimum flame height is observed in WR sandwich composites (Fig. 4). Thus CSM sandwich specimens are more vulnerable to the flame when compared to other sandwich specimens. This may be due to the fibre architecture in the case of CSM sandwich composites, which can promote flammability.

Fig. 5 (a) Post burnt PU Foam (200 Kg/m^3)

Fig. 5 (b) Post burnt PU Foam (100 Kg/m^3)

It is observed that the bare PU foams of lower densites of 100, 150 and 200 kg/m^3 typically show a strange behavior of bending during fire. Fig. 5 shows the photograph of post burnt bare PU foam of densities 200 and 100 kg/m^3. The specimens after burn show remarkable cracks on the surface of the foam. The bending behavior of lower density foams may be attributed to the spring action of the cell walls which are unburnt in the deeper part of the foam. But as the density of PU foam increases the foam does not afford to bend even after complete burning. The varied density of polyurethane foam affects the flammability behavior of PU foam. The varied PU foam density is caused by varying the proportion of chemicals and the foam is formed with the chemical bonding between polyol and MDI. While at formation, the core traps gases within the cells. The number of cells per unit area increases as the density of the foam increases, causing more gas entrapment in the closely arranged cell walls. In the case of lower density foams the trapped gas will be less and cell walls are regularly spaced like an array and this regular array is repeated [16]. Hence the lower density specimen takes prolonged time for flame extinction than the higher density foams. In the case of low density, during burning foam is converted into powder, where as in the case of high density, foam undergoes charring. Combustion of PU foam is also characterized by the formation of dark smoke with irritating aroma, justifies the formation of toxic gases. The results of Drysdale et.al 1985 [17] show that flammability is dependent on the chemical nature of the evolved gases, and that flammability can be altered with chemical additives or suppressants. Similar conclusions are made by Nyden et al. [18, 19].

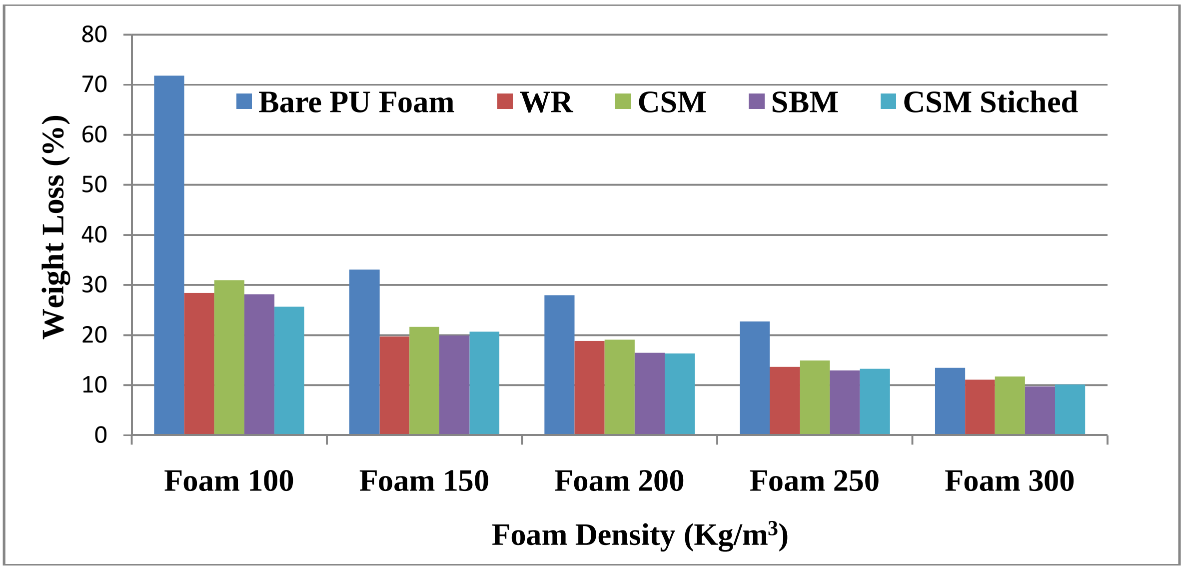

Fig. 6 Loss of Weight (%) V/s foam density

The weight loss in the burning of pure PU foam is much higher when compared to sandwich composites. Moreover weight loss is found to be less for high density PU foam (Fig. 6). In the case of sandwich composites the matrix and foam core are disintegrated in the vicinity of fire and the weight loss is mainly due to the combustion of resin and foam core during the burning process (Fig. 6). The weight loss is found to be much less compared to bare polyurethane foam. In case of sandwich specimens of lower density cores, the loss of weight is due to the loss of foam as crushed powder, but the higher density foam cored sandwich specimens offer stiff opposition to burning. In the case of post burnt sandwich specimens, fibres are clearly distinguished. This shows that fibres have not undergone burning during fire. The face sheet is completely involved in the burning, justifies the fact that the face sheet has more affinity for combustion. Thus in the present study, matrix and core are disintegrated in the vicinity of the fire.

It is observed that, the burnt resin is forced out of the fiber pores, and burn pressure causes the material to swell over its original volume. Cracks are formed on the surface of core material and low density foam cores are found to be bending while burning. CSM sandwich specimens show high weight loss followed by WR type, the weight loss with CSM (S) and CSM sandwich composites are found to be minimum (Fig. 6).

Fig 7 shows the photograph of post burnt sandwich specimen. In the present study, fire induced damages in sandwich composites are found to be decomposition and softening of the matrix and core, release of toxic gas, core cracking, pore formation, delamination and char formation.

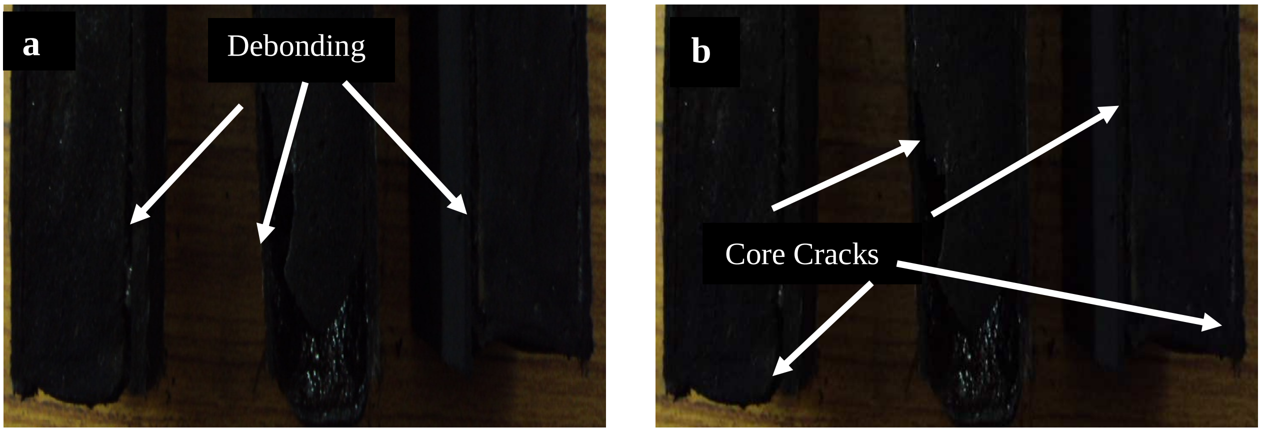

Fig.7 (a) Face sheet debonding in sandwich composites 7 (b) core crack in sandwich composites

The out gassing or deflation is followed by the delamination of the facet and in few cases, resulted in debonding from foam surface. Delamination during the fire is marked by an audible tearing or ripping sound and an observable bubble formation under the skin. The delamination occurred in all samples during fire and is between the stack-up layers rather than between foam- facet interfaces. After delamination, the trapped gas escapes through the specimen edges. Smoke and toxic gases are evolved from the combustion of matrix and foam during burning. Smoke generated from the test material is very sooty and dark. Ignition produces un pleasant aroma which is attributed to the formation of toxic fumes.

Burning rates for the specimens is presented in Table 3. Higher burning rates are observed in the vertical position. Burning rate decreased with increase in the density of foam core. The effect of fibre architecture on the burning rate is not significant. However CSM sandwich specimens show highest burning rate and CSM (S) composites lowest.

Table 3: Burning rates (mm/sec) in vertical (V) and horizontal (H) position

Sandwich Type	**Density in Kg/m^3**									
	100		**150**		**200**		**250**		**300**	
	V	**H**	**V**	**H**	**V**	**H**	**V**	**H**	**V**	**H**
WR	1.48	0.54	1.30	0.53	1.21	049	1.11	0.49	0.99	042
CSM	1.65	0.74	1.41	0.62	1.37	0.59	1.26	0.59	1.11	0.53
SBM	1.36	0.57	1.23	0.54	0.93	0.46	1.01	0.39	0.72	0.34
CSM (S)	1.06	0.49	1.09	0.48	0.87	0.43	1.19	0.36	0.86	0.30

The decomposition behavior of glass fibre reinforced vinyl ester composites has been reported by S Feih et.al. [20]. The weight loss on exposure to fire was mainly due to thermal decomposition of vinyl matrix. The laminates did not lose any weight or lose any heat at the lowest heat flux of 10 KW/m^2 i.e., temperature of 250° C. Thermo gravimetric analysis (TGA) revealed that vinyl ester did not degrade below 380° C. The laminate experienced low rate of mass loss & heat release at the heat flux of 25 KW/m^2 which heated the surface to about 440° C.

TGA showed that a significant portion of the matrix was decomposed at this temperature; however complete decomposition did not occur. The mass loss and heat release rates were much higher and the polymer matrix completely degraded when the laminate was tested at 50 and 75 KW/m^2 resulting in a surface temperature of about 600 - 800° C respectively [20].

The properties of fire damaged sandwich composites i.e., PVC core glass reinforced composites and phenolic cored glass reinforced phenolic sandwich composites were studied in detail by A. P Mouritz & C P Gardener [21]. They have reported that PVC- cored glass reinforced vinyl ester sandwich composites were severely damaged when exposed to fire. Phenolic cored glass reinforced phenolic sandwich composites was also damaged by fire with phenolic matrix to skin and phenolic foam core being thermally degraded to solid char. Poly Vinyl Core (PVC) sandwich composite did not ignite when the heat flux was below 15 KW/m^2, equivalent to surface temperature of about 475° C. Phenolic core was more resistant and did not ignite under 30 KW/m^2 (550° C). Exposing both to higher heat fluxes caused a rapid reduction to ignition times. At highest heat flux 100 KW/m^2, PVC core sandwich composites started burning within a few seconds where as ignition time for phenolic cored sandwich composites was much longer because of its superior flame resistance. In phenolic core sandwich composites the material is almost completely charred before it ignited. It is well known that PVC foam is thermally unstable compared to PU foam [22]. Even at low temperatures volatile products like HCl is given out. On the basis of the present experimental results, it can be inferred that behavior of PU foam cored sandwich composites under fire is superior to PVC sandwich composites and inferior to phenolic sandwich composites.

CONCLUSION

Fire characteristics of bare PU foam and PU foam cored sandwich composites have been studied and the following conclusions have been made.

1. The flammability in vertical mode is faster than the horizontal mode.
2. Lower density PU foams burn faster than higher density foams.
3. Combustion of PU foam is characterized by the formation of dark smoke with irritating aroma, justifies the release of toxic gases like CO_2.
4. Burning of the sandwich specimens result in delamination and debonding of facesheets from the core surface.
5. CSM sandwich composites are more vulnerable to fire compared to other sandwich composites.

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