Experimental Investigation on the Fire Performance of Corrugated Sandwich Panels made from Renewable Material

Avishek Chanda, Nam Kyeun Kim, Debes Bhattacharyya

***Abstract*—**The use of renewable substitutes in various semi-structural and structural applications has experienced an increase since the last few decades. Sandwich panels have been used for many decades, although research on understanding the effects of the core structures on the panels' fire-reaction properties is limited. The current work investigates the fire-performance of a corrugated sandwich panel made from renewable, biodegradable, and sustainable material, plywood. The bench-scale fire testing apparatus, cone-calorimeter, was employed to evaluate the required fire-reaction properties of the sandwich core in a panel configuration, with three corrugated layers glued together with face-sheets under a heat irradiance of 50 kW/m^2. The study helped in documenting a unique heat release trend associated with the fire performance of the 3-layered corrugated sandwich panels and in understanding the structural stability of the samples in the event of a fire. Furthermore, the total peak heat release rate was observed to be around 421 kW/m^2, which is significantly low compared to many polymeric materials in the literature. The total smoke production was also perceived to be very limited compared to other structural materials, and the total heat release was also nominal. The time to ignition of 21.7 s further outlined the advantages of using the plywood component since polymeric composites, even with flame-retardant additives, tend to ignite faster. Overall, the corrugated plywood sandwich panels had significant fire-reaction properties and could have important structural applications. The possible use of structural panels made from bio-degradable material opens a new avenue for the use of similar structures in sandwich panel preparation.

***Keywords*—**Corrugated sandwich panel, fire-reaction properties, plywood, renewable material.

I. Introduction

STRUCTURAL materials from renewable sources have become very popular in the recent times due to their environment friendly and sustainable natures and many studies have shown the possibility of using the same for different applications [1]. Transforming renewable sources into sandwich panel configurations can have significant advantages in specific strength and stiffness over solid panels having the same mass [2]-[7]. The limitations, however, lie in the less exposure of such panels, cost-effective manufacturing and understanding of the various mechanical and fire-related properties. This work is focused on the fabrication of a plywood-based sandwich panel with 3-layered corrugated cores and in eventually observing the fire-reaction properties of the material.

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Previous studies [8]-[10] have shown that plywood structures can be formed into permanent desired profiles by using the ideal forming parameters and efficiently eliminating the viscoelastic cells at the forming plane. This observation has resulted in the application of the forming parameters to form corrugated core sandwich panels for the current study. The sandwich panels have been studied to give superior bending stiffness through the application of face-sheets because of the introduction of the high in-plane properties along with the core structure which has adequate shear and out-of-plane properties [11]. The use of sandwich panels can be primarily found in the aircraft industry, where weight is a primary concern and a high strength-to-weight ratio is required [5]. The sandwich panels have also been applied in the construction and transportation industries due to their added benefit in insulation and impact resistance [12]. Although the benefits provide a substantial advantage for applications of sandwich structures, they are primarily made from non-renewable polymeric materials. With the growing concern about the environmental impact caused by the non-renewable sources, the natural and bio-degradable materials are slowly making their way into the various applications.

Wood is a natural, biodegradable, eco-friendly, sustainable and renewable material with excellent specific strength-to-weight ratios. There are quite a few researches on studying the mechanical side of the sandwich structures and cores made from plywood and other wood related materials [13], [14]. The plywood-based sandwich panels have been reported to have major advantages over polypropylene (PP) based counterparts, with regards to the core shear properties, structural tensile strength and other mechanical aspects [4]. The current work focuses on preparing a 3-layered corrugated sandwich panel and investigating the fire-reaction properties of the same under a bench-scale testing method. A detailed comparison of the corrugated and honeycomb sandwich cores and panels between plywood and flax fiber reinforced fire retardant PP material systems have been reported in [1]. This study is an extension where three-layered corrugated sandwich panels had been tested to observe the total heat release rate (HRR), the peak heat release rate (PHRR), the time to ignition (tIg), the time to PHRR (tPHRR), the total smoke produced, the total heat released, the total heat evolved and the flame-out time (tfg). The results point towards the possibility of using the plywood structures in structural applications, even where fire is involved, providing another avenue where renewable and sustainable materials can replace the engineered composites and non-renewable material systems.

II. Materials and Methods

A. Sample Preparation

Plywood made from Radiata Pine (*Pinus radiata* D. Don) was acquired from a commercial supplier, Plyman Auckland. The plywood sheets were composed of three veneer layers, each having 0.6 mm thickness and assembled in 0°/90°/0° orientation. The veneers were glued with 2-pot poly-vinyl acetate (PVA), which was applied at about 250 g/m^2 on each surface of the veneers. The overall thickness of the plywood was 1.8 mm, which were cut into 300×300 mm^2 panels for forming the corrugations, Fig. 1 (a). A temperature controlled press was used to form the corrugations on the plywood samples, giving a sinusoidal profile to them. The temperature of the press was maintained at 190 °C, which was the highest operating temperature. The plywood samples, as per the literature, was first soaked in a water-bath, kept at 70 °C, for 60 s. Eventually, the samples were placed in the hydraulic press, Fig. 1 (b), and held in the pressed position for 90 s. Samples of 100×100 mm^2 were then cut from both corrugated and flat sheets and then assembled in the orientation shown in Fig. 1 (c). PVA glue was again used to perform the assembly and the structures were clamped for 24 h under a pressure of 1 kPa. The final thickness of the structure was observed to be 31 mm, including the face sheets.

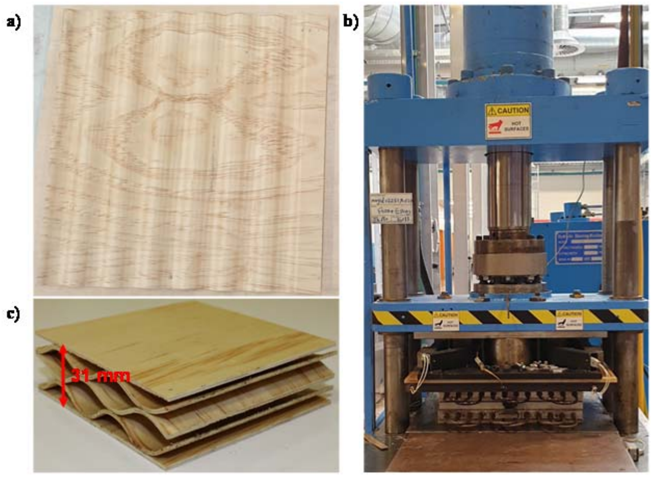

Fig. 1 (a) The press used for creating the corrugated panels, (b) the corrugated panels formed and (c) the 3-layered corrugated sandwich panel made of Radiata Pine plywood

B. Experimental Set-Up – Cone Calorimeter

The fire performance of the sandwich panel was evaluated under an external heat flux of 50 kW/m^2 in a cone-calorimeter apparatus (FTT Limited, East Grinstead, United Kingdom) in the horizontal testing orientation. The method involves a bench-scale testing procedure for observing the various fire reaction properties, such as PHRR, time to PHRR, TSP, CO and CO_2 yield, tIg, tfg, mass loss and other vital parameters of concern [15]. ASTM E1354-14 standard [16] was followed for the sample preparation and setting up the test rig. All the samples were pre-conditioned in an environmental chamber at a temperature of 23 °C and a humidity of 50%, as per the standard specifications. Five samples were tested to observe the average and to eliminate the aberrations in the final results.

III. Results and Discussions

HRR response is shown in Fig. 2 (a) and it could be observed that the initial response is similar to that of a thermally thin material [17], influenced by the 1.8 mm thin plywood face-sheet on the top. The trend experienced during the radiant heating phase, by the corrugated sandwich panels, showed around five peaks (3 prominent and 2 minute jumps), equivalent to the number of layers in the entire sample. Therefore, it could be concluded that the HRR response is a unique one, which can only be observed from a 3-layered corrugated sandwich panel. The ignition time for the samples was recorded at 21.7 s, Table I, which is significantly higher compared to PP based fire-retardant (FR) materials (Flax-FRPP: 16 s) and even other FR samples [1], [18]. Moreover, the samples were perceived to burn for a very long time (509.7 s) before flame-out, a noteworthy aspect which could be critical for evacuation. The PHRR was reported to be around 421.8 kW/m^2, which again is substantially on the lower side, compared to about 1200 kW/m^2 for PP [19] and 469.5 kW/m^2 for flax fiber reinforced fire-retardant (flax-FRPP) corrugated sandwich panel [1]. Furthermore, the time to PHRR (t_{PHRR}) was also about 35 s which was longer than other polymeric composites. Additionally, apart from the initial peak, the HRR response showed significantly lowered and stable response in most of the burning phase, with the highest HRR of about 220 kW/m^2 being recorded. The sharp drop in HRR is analogous to the response of FR materials, which could be partially observed in non-treated renewable plywood samples. Fig. 2 (b) illustrates that the total heat released by the sample during the burning phase, which shows a THE of 67.4 MJ/m^2, was almost equivalent to the fire retardant flax-PP sandwich panels having a time to flame-out of only 370 s [1]. Hence, the plywood-based sandwich panel was perceived to have less amount of heat release, which could again be a great advantage for structural application. The highest amount of smoke produced was interestingly only 2.3 m^2 at the time of flame-out, Fig. 3 (a) and Table I, an attribute which has one of the better responses in plywood and wood-based structures. The less amount of smoke would significantly aid in evacuation procedure by increasing visibility and subsequently aiding in faster evacuation. The mass loss was recorded to be about 91.82%, with 18.18% char being formed from the burning. The gradual mass loss could also be perceived, Fig. 3 (b), preventing catastrophic failure of the structure under fire if used in structural applications.

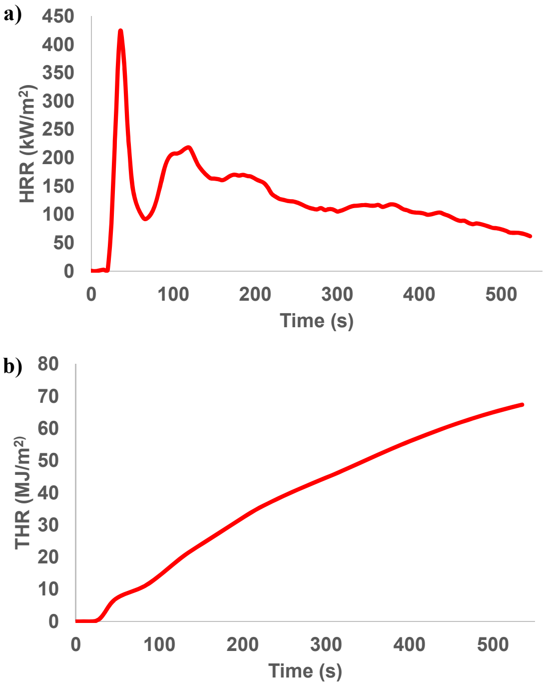

Fig. 2 (a) The total HRR and (b) the total heat released (THR) trends of the three-layered corrugated sandwich panels

TABLE I
FIRE REACTION PROPERTIES OF THE THREE-LAYERED CORRUGATED SANDWICH PANEL

Time to ignition (s)	PHRR (kW/m^2)	Time to PHRR (s)	Time to flame-out (s)	Total smoke production (m^2)	Total heat evolved (MJ/m^2)
21.7	421.8	35	509.7	2.3	67.4

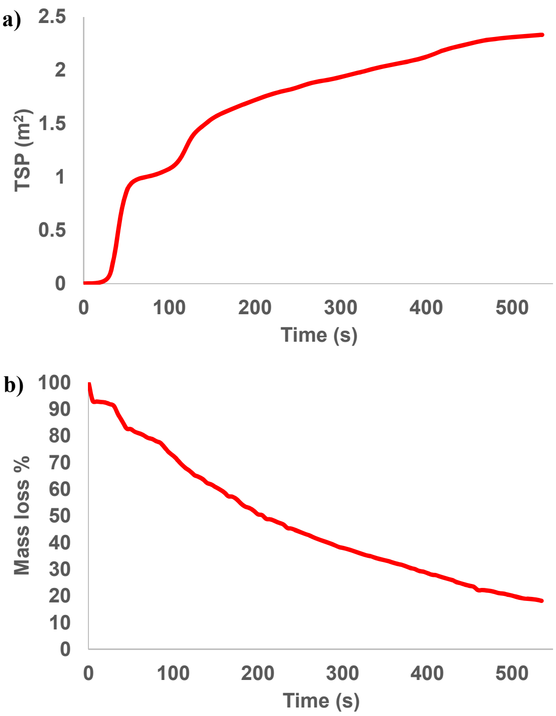

Fig. 3 (a) The total smoke produced (TSP) and (b) the mass loss percentage curves of the three-layered corrugated sandwich panels

The residual char formation, Fig. 4, can be detected to be noteworthy for a material which has no external FR element. The 18.18% char residue is almost similar to that of flax-FRPP sandwich structures [1], again a major advantage for the wooden materials because of the presence of relatively higher amount of lignin compared to other natural fibers. Moreover, the residue had the structural shape of the corrugations intact even after complete flameout, Fig. 4 (a). The overall results demonstrated that the core structure is one of the major factors for determining the fire-reaction properties of the sandwich panels and the unique behavior of the different cores can benefit the selection of the core-type for different structural and semi-structural applications.

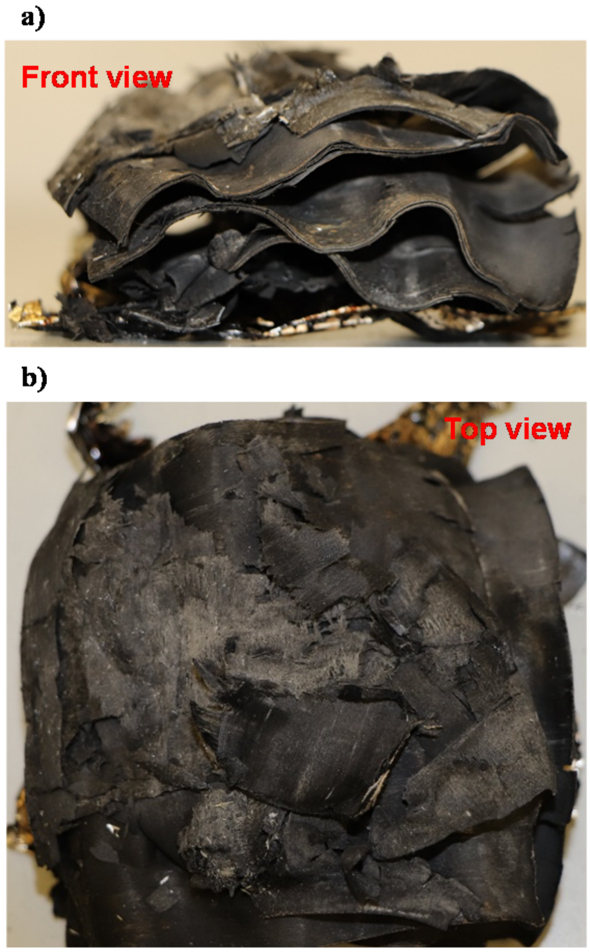

Fig. 4 The front and top views of the char produced by the sandwich panel

IV. CONCLUSIONS

The study aids in performing a comprehensive fire performance study complementing the previous study on corrugated and honeycomb sandwich panels and reporting the responses for a bigger structure with more corrugated layers in the core. The heat release trend was observed to be unique and was concluded to represent a 3-layered corrugated sandwich panel made from plywood. PHRR was perceived to be only 421.8 kW/m^2. Furthermore, the time to ignition, 21.7 s, was quite higher compared to FR materials reported in the literature. Moreover, the burning time of 509.7 s was also quite extended where the heat release was low and stable for the majority of the burning phase. The highest amount of smoke produced was only 2.3 m^2, which was extremely low for such a long burning phase. Therefore, the plywood structures showed significant fire-reaction properties by taking a long time to ignite, producing less heat, having very limited smoke and a substantial amount of char formation. Thus, the study helps to report the fire-reaction properties of three-layered corrugated sandwich panels made from renewable, biodegradable, sustainable and environmentally friendly material system of plywood, for possible structural applications with noteworthy advantages over the synthetic or engineered materials.

Acknowledgment

The authors would like to acknowledge the contribution of the CACM department and the technical staffs for their continuous support and contribution towards the experimental findings. The authors would also like to thank Ministry of Business, Innovation and Employment (UOAX1415) for their continuous support and funding to carry out the research works.

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