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LIFE CYCLE ASSESSMENT OF GLASS/ POLYESTER LAMINATES USED IN THE SHIPBUILDING INDUSTRY AND ITS FIRE BEHAVIOR

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ABSTRACT: The aim of this study is to assess the environmental performance of the manufacturing process of glass/polyester laminates as well as estimate their fire behaviour and smoke release. The Life Cycle Assessment was conducted according to the ISO14040/44 standard by using the CML-IA 2000 Baseline Midpoint method. The cone calorimeter study was conducted using a cone calorimeter method according to ISO 5660. The tests were performed under 25 kW/m^2 heat flux 50 kW/m^2. The results showed that according to the requirements of the Fire Test Procedure (FTP) Code examined, laminates in this form cannot be used in some applications. The LCA study showed that the highest impact is attributed to marine aquatic ecotoxicity (88.3%), with the highest contribution of the unsaturated polyester resin and the glass fibre.

KEYWORDS: glass/polyester laminates, life cycle assessment, cone calorimeter, Fire Test Procedures (FTP) Code

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Introduction

Fiber reinforced composites, due to their high mechanical properties and durability, have been commonly used over the last few years. However, its manufacturing process and poor recyclability are the cause of a concern (Gkoloni & Kostopoulos, 2021). One of the main contributors to environmental pollution is manufacturing, especially in terms of air pollution (Rödger et al., 2021). The life cycle assessment (LCA) is a tool for the integration of environmental concerns into the product development (Segovia et al., 2019). This method also allows the identification of critical points in the life cycle and the selecting of the areas that may be improved (Flasińska et al., 2018). It addresses the complex interactions between products and the environment (Kukfisz & Maranda, 2014). The assessment of the environmental impact of the manufacturing process of glass/polyester laminates will allow us to identify the most damaging factors within the concerned impact categories and examine possibilities for their improvement.

Fire safety is one of the major issues of ships. Ongoing advances in fire detection technology, fire suppression equipment and firefighting techniques can minimise fire damage. However, materials used for the construction and other elements of ships can also affect the fire risk. Metallic materials are widely replaced by non-metallic polymers, which may release a lot of heat, smoke and toxic gases and thus reduce fire safety (Hiltz, 2011). Therefore, materials used in shipbuilding are strictly regulated by national standards and requirements. The aim of this study is an analysis of the heat and smoke release of selected laminates applied in shipbuilding and a comparison with existing requirements for fire-restricting materials for high-speed craft.

An overview of the literature

Composites were introduced to the marine industry after World War II, and they are used in all areas of the marine sector up to the present time. Because salt and seawater may be extremely damaging to steel, aluminium and wood used for watercraft, composites were designed to solve occurring corrosion problems. Due to the high corrosion and fatigue resistance of thermoset composites, their application may significantly reduce maintenance requirements.

In addition to mentioned corrosion resistance, other benefits of thermosetting resins are good strength-to-weight ratio, dimensional stability, lighter weight compared to materials traditionally used before, sound baffling and high levels of acoustic transparency, the possibility to design complex shapes and greater stiffness and stability (Rubino et al., 2020).

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Currently, laminates are considered a classic structural solution in smaller ships and boats. In larger vessels, yachts and boats, composites are used for the main structural elements. However, in ships, their application is limited to various structural and non-structural elements (Bolf et al., 2020).

The diversity of matrices and reinforcements enables the manufacture of composites with specific properties suitable for their application. However, the most commonly used materials for marine composites are unsaturated polyester resin as a matrix and E-glass fibres as a reinforcement. Other thermosetting resins, such as phenolic, epoxy and vinyl-ester resins and thermoplastic polymers, such as polypropylene, polyamide, polyester and PEEK (polyether ether ketone), also may be used as a matrix. For the reinforcement, glass, carbon and aramid fibres are the most often used (Barsotti et al., 2020).

Due to the fact that glass/polyester laminates are entirely synthetic and contain petroleum-based thermoset polymer matrix, they are non-biodegradable and may pose an environmental hazard. They may contribute to global warming and promote toxic environmental effects (Ead et al., 2021).

Glass/polyester laminates, besides their various advantages, also pose a high fire hazard. Its flammability is mainly ascribed to the thermal decomposition of a polymer matrix because glass fibres are non-combustible. Glass/polyester laminates produce a lot of heat and flammable, volatile compounds such as carbon monoxide, methane and other low molecular weight compounds when exposed to high temperatures. Improving the flame retardancy of these materials is not obligatory; however, in some applications with high flammability requirements, a proper level of fire safety needs to be achieved (Dowbysz et al., 2021).

The International Convention for Safety Of Life At Sea (SOLAS), established within The International Maritime Organization (IMO), focuses on the mitigation of risks at sea in order to protect human life. SOLAS provides necessary mitigation measures by identifying and examining risks. Chapter II-2 of SOLAS, with the associated supporting Fire Safety Systems (FSS) Code and Fire Test Procedure (FTP) Code, focuses on the fire risk (Joseph & Dalaklis, 2021).

The FTP Code refers to various fire test procedures, including non-combustibility test, smoke and toxicity test, tests for A, B, and F class divisions, test for fire door control systems, test for surface flammability, test for vertically supported textiles and films, test for upholstered furniture, test for bedding components, and test for fire-restricting materials and division of high-speed craft. Part 10, Appendix 2, describes fire test procedures for heat release, smoke production and mass loss rate for materials used for furniture and other components of high-speed craft according to ISO 5660-1 Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1:

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Heat release rate (cone calorimeter method) and ISO 5660-2 Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 2: Smoke production rate (dynamic measurement)(International Maritime Organization, 2012). The criteria for fire-restricting materials are as follows:

- the time to ignition should be greater than 20 s,
- the average heat release rate over a 30 s period of time should be 60 kW/m^2 at the maximum,
- the total heat release should be 20 MJ/m^2 at the maximum,
- the average smoke production rate should be 0.005 m^2/s at the maximum.

Materials and research methods

Preparation of glass/polyester laminates

The glass/polyester laminates with a top gelcoat layer were prepared using a Norpol pre-accelerated orthophthalic unsaturated polyester resin (UPR), polyester gelcoat BUFA GC-S green or Norpol SVG white, Luperox organic peroxide as the hardener, and 450 g/m^2 fibreglass mat.

The unsaturated polyester resin undergoes free-radical polymerisation with styrene, which is the resin's reactive solvent - crosslinking monomer. Individual stages of the process of obtaining glass/polyester laminates (lining of the gelcoat layer and application of the resin layer with the mat) were performed before the unsaturated polyester resin started to crosslink, i.e. within 25-45 min.

The laminates were prepared manually using the contact method of lining the gelcoat layer and then applying the resin to the individual layers of the glass mat. Polyethylene terephthalate film was placed on the cleaned glass mould as a release layer. Five fragments of glass mat with dimensions of 250 mm x 250 mm were prepared. An appropriate amount of hardener was added to the polyester gelcoat. Then the mixture was vented in a glass desiccator under 20 mbar pressure for 2 min to remove air bubbles. The gelcoat was applied directly onto the terephthalic film using a doctor's blade. A gelcoat layer of 0.75 mm thickness was obtained. It was cured for 60 min at a temperature of 22°C. Next, the first fragment of the glass mat was placed on the cured gelcoat layer and saturated with resin with an appropriate amount of hardener. After thorough saturation, another layer of the mat was applied. The procedure was repeated for each of the 5 glass mat fragments. After the last one was saturated, the entire laminate was covered with terephthalic film, followed by a glass plate, and loaded to form the laminate. Spacers 3 mm high were used between the glass plates. The laminate was left to cure and

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season for 24 hours at a temperature of 22°C. The 3 mm thick crosslinked polyester-glass laminates with an outer gelcoat layer were obtained. The laminates were cut into shapes suitable for testing. The laminate formulations are shown in Table 1.

Table 1. Formulations of laminates

Sample	Gelcoat [g] Norpol SVG	Gelcoat [g] BUFA GC-S	Hardener [g]	UPR [g] Norpol 1	UPR [g] Norpol 2	Hardener [g]	Fiberglass [g]
Laminate 1	56.30	-	1.10	261.30	-	5.33	140.60
Laminate 2	56.30	-	1.10	-	261.30	5.33	140.60
Laminate 3	-	56.30	1.10	261.30	-	5.33	140.60

The LCA method and tool

The evaluation of the potential environmental impacts of manufacturing of glass/polyester laminates was performed using life cycle assessment (LCA) methodology according to the ISO14040/44 standard. The LCA analysis consisted of four interrelated steps: goal definition and scope, inventory analysis, impact assessment and improvement assessment. The LCA analysis was modeled in SimaPro LCA software version 9.1 (PRé Sustainability B.V, Netherlands).

Table 2. Midpoint impact categories for the CML Baseline method

Name of the impact category	Abbreviation of the impact category	Unit
Abiotic depletion potential	ADP	kg Sb
Abiotic depletion potential (fossil fuels)	ADP (FF)	MJ
Global warming potential	GWP100a	kg CO_2
Ozone layer depletion potential	ODP	kg CFC-11
Human toxicity potential	HTP	kg 1,4 DCB
Freshwater aquatic ecotoxicity potential	FAETP	kg 1,4 DCB
Marine aquatic ecotoxicity potential	MAETP	kg 1,4 DCB
Terrestrial ecotoxicity potential	TETP	kg 1,4 DCB
Photochemical oxidation potential	POF	kg C_2H_4
Acidification potential	AP	kg SO_2
Eutrophication potential	EP	kg PO_4

Source: authors' work based on Di Giuseppe et al. (2020).

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The CML-IA method developed by the Center of Environmental Science of Leiden University in The Netherlands was applied in this study to assess the environmental load of the glass/polyester laminates over the whole life cycle. The CML-IA Baseline method elaborates the problem-oriented (midpoint) approach. All impact categories in the CML Baseline method defining the environmental profile are related to the 11 recommended baseline indicators presented in Table 2.

The purpose of this LCA study is to assess and quantify the environmental impact of the manufacturing process of glass/polyester laminates used in the shipbuilding industry. The functional unit is defined as the manufacturing of a 250 mm × 250 mm × 3 mm laminate plate. For the scope of the study a "cradle to gate" LCA is carried out. The system boundaries are presented in detail in Figure 1.

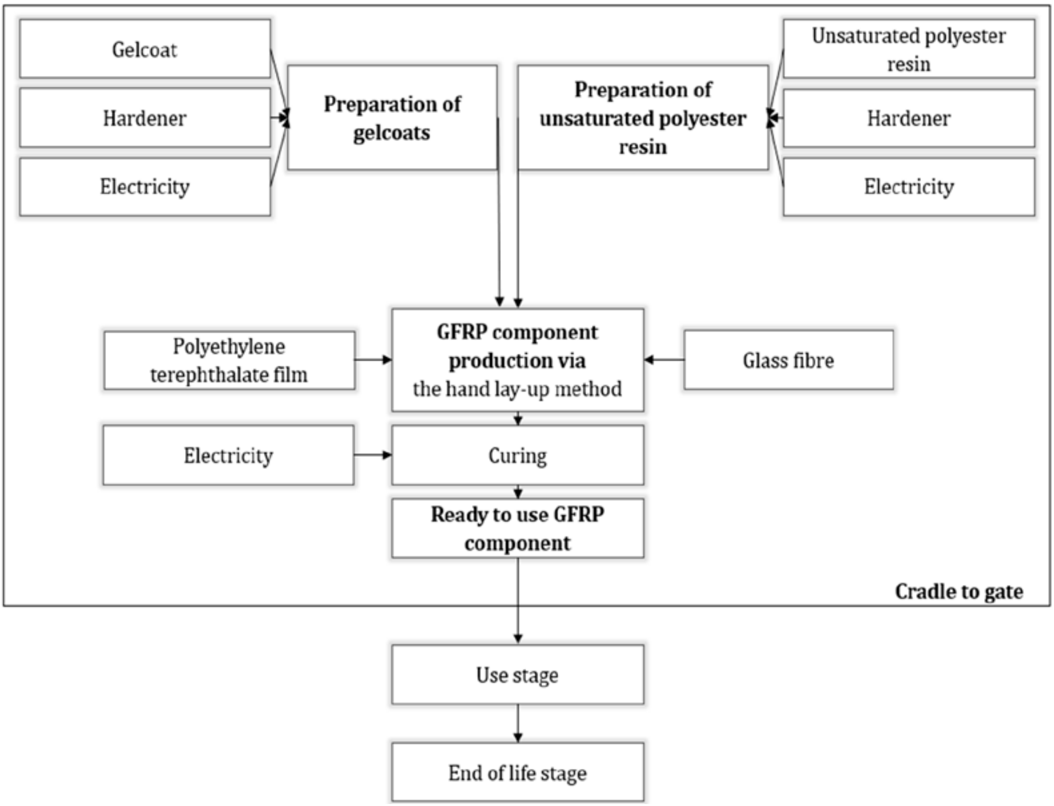

Figure 1. System boundaries for glass/fibre polyester laminates

The LCA was based on primary data from the laboratory scale experiments, where the optimisation of power and resources was not straightforward. In an industrial scale, the energy consumption and environmental load of the manufacturing process of glass/polyester laminates will be lower. The raw materials were orthophthalic unsaturated polyester resin (0.261 kg), glass fibre (0.140 kg), polyethylene terephthalate film (0.108 kg), methyl ethyl ketone peroxide (0.006 kg) as well as gelcoat (0.056 kg). Gelcoat was modelled using 0.75 kg isophthalic acid-based UP resin, 0.1 kg of titanium dioxide, 0.05 kg of aluminium hydroxide, 0.05 kg of feldspar, 0.05 kg of calcium carbonate and 0.02 kg of chemical, organic. Manufacturing processes involved the cutting of the glass fibre and mixing of the gelcoat and the hardener, venting of the gelcoat mixture - electricity for the pump to achieve 20 mbar (consuming 0.037 kWh of electricity), laminating via the hand lay-up, conditioning of chamber (24 hours, 22°C, consuming 252 kWh of electricity) as well as cutting of the laminate (consuming 0.325 kWh of electricity). The functional unit of 1 kg of glass/polyester laminate was chosen as a representative of the laboratory-scale experiments.

The cone calorimeter test

Fire behaviour was assessed on a cone calorimeter (Fire Testing Technology, East Grinstead, UK) according to ISO 5660-1:2015 Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement). The test specimens (100 mm x 100 mm x 5 mm) were exposed horizontally to an external heat flux of 25 kW/m^2 and 50 kW/m^2. Spark igniter was used to ignite the pyrolysis products. Measurements were conducted in three repetitions.

Results and discussion

The Life Cycle Assessment

The Life Cycle Impact Assessment (LCIA) was carried out for a glass/polyester panel using SimaPro 9.1 according to data obtained from the inventory analysis.

Table 3 presents the results obtained using the CML Baseline method.

The Figure 2 presents the relative contributions of material production to each impact category.

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Table 3. LCIA results were calculated from the CML Baseline method

Impact category	Unit	PTFE film	Gelcoat	UPR	Hardener	Glass fibre	Electricity	Total
ADP	kg Sb eq	7.24E-14	3.41E-14	1.73E-13	1.29E-15	1.73E-13	3.72E-12	4.17E-12
ADP (fossil fuels)	MJ	2.33E-13	1.18E-13	6.62E-13	1.02E-14	1.17E-13	6.19E-11	6.31E-11
GWP100a	kg CO_2 eq	6.65E-14	3.76E-14	1.87E-13	2.04E-15	5.84E-14	3.57E-11	3.6E-11
ODP	kg CFC-11 eq	1.83E-16	2.80E-16	1.65E-15	7.77E-18	3.17E-16	8.91E-14	9.15E-14
HTP	kg 1,4-DCB eq	3.74E-14	5.58E-14	3.44E-13	6.83E-16	4.39E-14	9.60E-12	1.01E-11
FAETP	kg 1,4-DCB eq	3.15E-13	2.20E-13	9.58E-13	6.67E-15	2.60E-13	1.45E-10	1.46E-10
MAETP	kg 1,4-DCB eq	2.84E-12	2.60E-12	8.99E-12	5.54E-14	4.12E-12	2.37E-09	2.39E-09
TETP	kg 1,4-DCB eq	1.02E-14	6.25E-15	3.12E-14	1.63E-16	1.08E-14	7.27E-12	7.33E-12
POF	kg C_2H_4 eq	9.09E-15	3.78E-14	2.19E-13	2.62E-16	8.03E-15	3.56E-12	3.83E-12
AP	kg SO_2 eq	4.53E-14	4.19E-14	1.43E-13	1.13E-15	6.75E-14	2.71E-11	2.73E-11
EP	kg PO_4 eq	2.69E-14	2.31E-14	1.16E-13	7.13E-16	3.98E-14	2.59E-11	2.61E-11

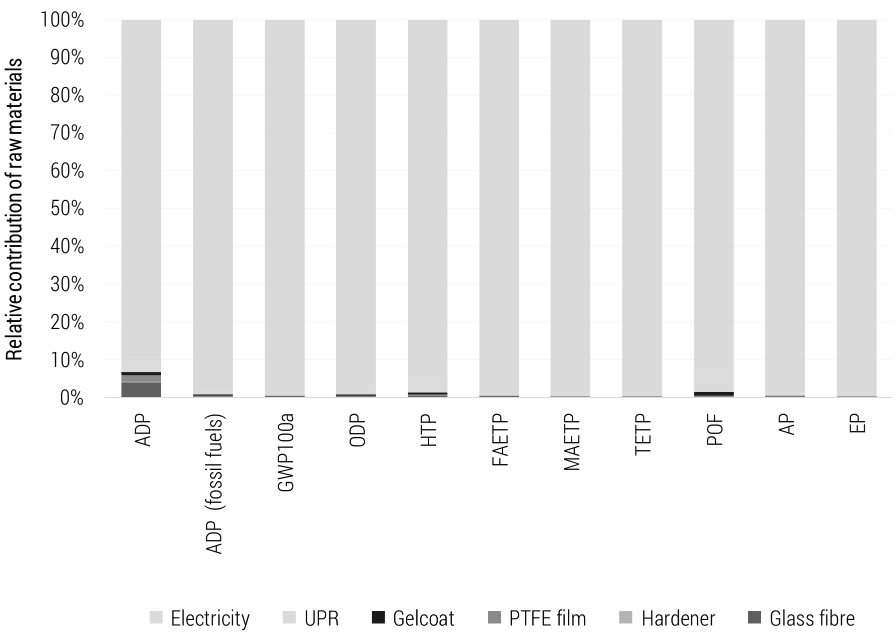

Figure 2. Relative contributions of material production [%] to each impact category

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For all impact categories, electricity has the highest contribution (89% and above of the overall impact), and the hardener has the lowest contribution (0.03% and less of the overall impact). For each impact category the authors examined the most impacting materials.

The abiotic depletion of resources was considered as the loss of availability of natural elements (ADP) and as the loss of the availability of fossil fuels (ADP (fossil fuels)) (Van Oers et al., 2002).

ADP is the impact category with the highest contribution of UPR (1.73E-13 kg Sb) and glass fibre (1.73E-13 kg Sb), standing for the 4.14% each of the overall impact. In comparison, the contribution of the UPR and glass fibre to ADP (fossil fuels) is significantly lower (1.05% and 0.19%, respectively, of the overall impact). Lower values of ADP (fossil fuels) comparing to ADP were observed also for the PTFE film, gelcoat and hardener. Moreover, the glass fibre, PTFE film and hardener have the highest relative contribution to ADP among all impact categories.

The global warming potential is a category quantifying the influence of energy technologies on the climate (Lan & Yao, 2022). The highest impact is observed for the UPR (1.87E-12 kg CO_2). Significantly lower values of GWP100a were observed for the PTFE film (6.65E-14 kg CO_2) and glass fibre (5.84E-14 kg CO_2). The hardener and the gelcoat have the lowest contribution of the 0.11% of the overall impact.

The reduction of an ozone layer caused by the halocarbons is represented by the ozone layer depletion potential (Farinha et al., 2021). The UPR is the material that contributes the most to the ODP (1.65E-15 kg CFC-11). It is responsible for 1.8% of the overall impact. Other materials, including gelcoat, glass fibre and PTFE film, have HTP values of 3.17E-16, 2.8E-16 and 1.83E-16, respectively.

The impact of the chemicals released into the environment on the human health, based on their toxicity and dose, is the human toxicity potential (Hertwich et al., 2001). The obtained HTP values of materials are high comparing to other impact categories. The most impacting UPR has a HTP value of 3.44E-13 kg 1,4-DCB (3.41% of the overall value). The gelcoat, glass fibre and PTFE film cause 1.36% of the overall impact.

The highest impact to the freshwater aquatic ecotoxicity is observed for the UPR (9.58E-13 kg 1,4-DCB), standing for the 0.65% of the overall impact. Significantly lower values of FAETP were observed for the PTFE film (3.15E-13 kg 1,4-DCB), glass fibre (2.60E-13 kg 1,4-DCB) and gelcoat (2.20E-13 kg 1,4-DCB).

The impact of the toxic substances on the marine ecosystem is described by the marine aquatic ecotoxicity potential (Heijungs & Ligthart, 2004). The MAETP values are similar to those obtained for the TETP category, with a slight decrease of the UPR impact (from 0.43% to 0.38% of the overall impact) and slight increase of the glass fibre impact (from 0.15% to 0.17% of the overall impact). Moreover, the electricity has the highest relative contribution to MAETP among all impact categories.

The impact category that describes an adverse effect of toxic substances on the terrestrial ecosystems is a terrestrial ecotoxicity potential (Abdou et al., 2020). The most impacting is the UPR which implies a 0.43% of the overall impact (3.12E-14 kg 1,4-DCB). A hardener and a gelcoat have the lowest contribution of 0.09% of the overall impact.

The photochemical oxidation potential is related to the generation of the photochemical or summer smog by volatile organic compounds and NOx (Bałdowska-Witos et al., 2021). The UPR and gelcoat cause the 6.71% of the overall impact (2.19E-13 kg C_2H_4 and 3.78E-14 C_2H_4 respectively). Moreover, the gelcoat and the UPR have the highest relative contribution to POF among all impact categories.

Acidification is caused by the substances that supply or release the hydrogen ions or promote the leaching of the anions. The occurring increase of the acidity induce environmental problems, e.g. the acid rain (Jacob-Lopes et al., 2021). The AP is the impact category with the highest contribution of UPR and glass fibre (0.52% and 0.25% of the overall impact respectively). The lowest AP of 1.13E-15 was observed for the hardener (0.04% of the overall impact).

The most prevalent water quality drawback is an aquatic eutrophication (Berberich et al., 2019). The eutrophication is caused by the increased availability or usage of nutrients, which increases primary productivity. The main controlling nutrients are phosphorus and nitrogen (Hupfer & Hilt, 2008). The UPR has the highest EP of 1.16E-13 kg PO_4 eq. (0.44% of the overall impact). The lowest EP is observed for the hardener (7.13E-16 kg PO_4), the gelcoat (2.31E-14 kg PO_4) and the PTFE film (2.69E-14 kg PO_4).

The obtained results showed that the marine aquatic ecotoxicity potential is the main impact factor of the manufacturing process of glass/polyester laminates. It accounts for the 88.3% of all environmental impact indicators. Significantly lower impact is observed for the freshwater aquatic ecotoxicity, abiotic depletion (fossil fuels), and global warming potentials accounting for the 5.4%, 2.3% and 1.3% of all impact categories.

The cone calorimeter test results

Cone calorimeter tests provided data on the combustion behavior of laminates under real fire conditions. Mean values of the three measurements of parameters including time to ignition (TTI), peak heat release rate (pHRR), time to pHRR (t_{pHRR}), heat release rate at 180 s after ignition (HRR_{180s}), total heat release (THR), total smoke release (TSR), smoke extinction area (SEA), yield of CO (CO-Y) and residue yield at 1200 s are summarised in Table 4.

Table 4. Cone calorimeter data of laminates

Sample	Irradiance [kW/m^2]	TTI [s]	pHRR [kW/m^2]	t_{pHRR} [s]	HRR_{180s} [kW/m^2]	THR [MJ/m^2]	TSR [m^2/m^2]	SEA [m^2/kg]	CO-Y [kg/kg]	Residue Yield [%]
Laminate 1	25	42	120.08	240	117.02	30.1	116.5	26.4	4.359	27.80
Laminate 2		64	101.52	254	97.78	24.2	123.6	31.8	4.978	31.33
Laminate 3		49	120.19	70	119.28	29.5	78.1	18.3	4.577	27.96
Laminate 1	50	12	162.97	176	161.95	33.9	101.5	24.6	3.585	38.35
Laminate 2		22	142.03	196	140.45	28.3	75.2	16.7	5.064	29.94
Laminate 3		14	182.44	144	78.43	27.9	109.3	24.4	4.350	38.89

The TTI defines the ease of ignition of a sample. It represents the time needed to reach the pyrolysis temperature and to produce a critical concentration of flammable gases (Benzarti & Colin, 2013). At a lower irradiance level, the TTI is higher for all laminates. The TTI of laminate I is 42 s, which is the lowest of all the samples at a 25 kW/m^2 irradiance level. The TTI of laminates II and III is higher by 7 s and 22 s, respectively. At higher irradiance level, TTI is significantly lower for all laminates. The lowest value is observed for laminate I (12 s). Slightly higher TTI is observed for laminate III (14 s). The highest value of 22 s is observed for laminate II. Thus the observed TTI values indicate that laminate II is the most difficult to ignite under combustion. However, TTI is a rough indicator for flammability since it depends on various parameters, including thermal conductivity, heat capacity and the density of the material (Schartel & Hull, 2007).

Heat release rate (HRR) curves at irradiance level of 25 kW/m^2 and 50 kW/m^2 are shown in Figure 3 and Figure 4, respectively.

One of the most important parameters needed for the fire hazard evaluation of materials is the HRR, as it provides data of the fire growth, including heat release and production of gaseous products (Marquis et al., 2013).

As can be seen in Figure 1, the HRR curves for laminates I and III is similar. However, laminate III has the highest pHRR (120.19 kW/m^2) of all samples. The t_{pHRR} is achieved at the shortest time (70 s), which indicates its highest risk under combustion. The pHRR of laminate I, coincident with the subsequent peak on the HRR curve of laminate III, has a similar value (120.08 kW/m^2) but is achieved (only) later at 240 s. The pHRR of laminate II (101.52 kW/m^2) is the lowest and occurs at the very latest at 254 s.

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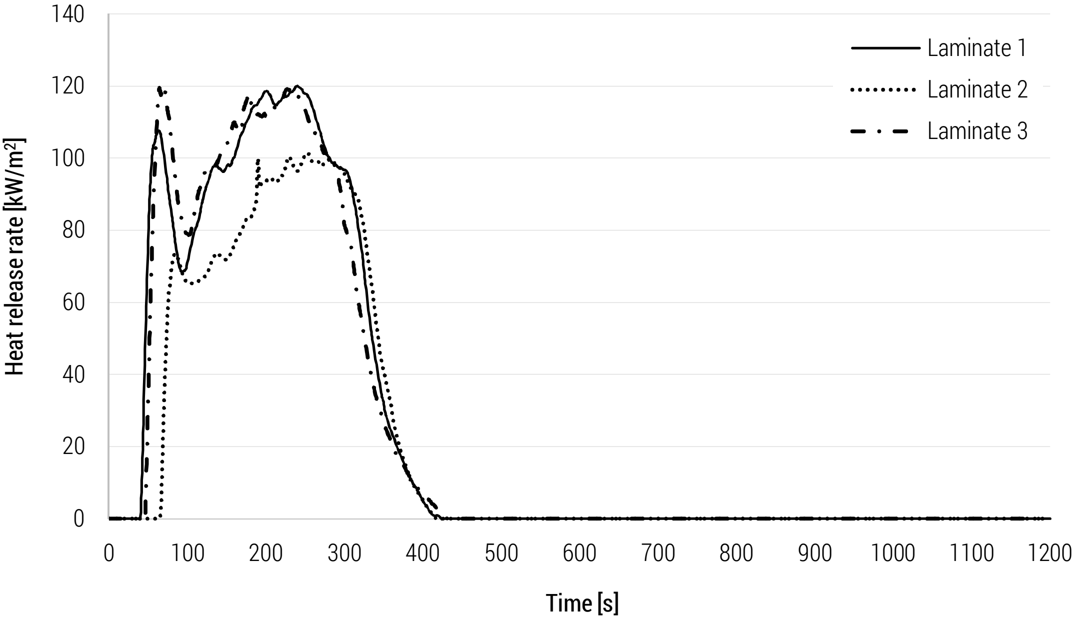

Figure 3. HRR curves of laminates under irradiance of 25 kW/m^2

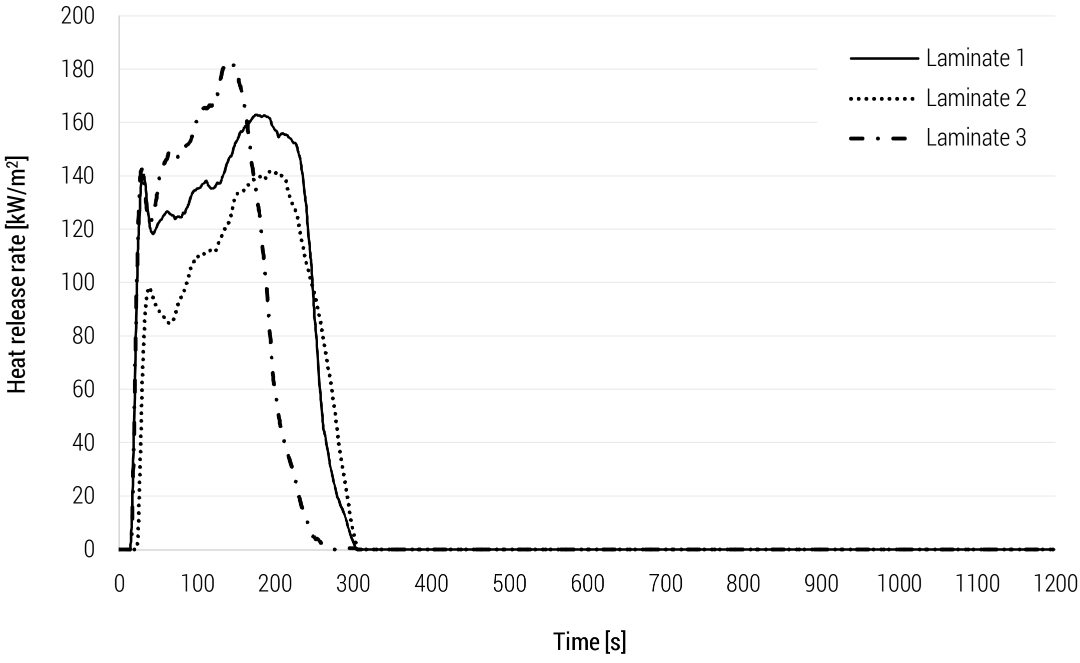

Figure 4. HRR curves of laminates under irradiance of 50 kW/m^2

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At the irradiance of 50 $kW/m^{2,}$ HRR curves of laminates are more diverse, as can be seen in Figure 4. Measurements taken at the higher heat flux show the increase of pHRR for all samples. The highest pHRR was observed for laminate III (182.44 kW/m^2). The pHRR values lower by 11% and 22% were observed for laminates I and II, respectively.

Due to the fact that in the initial period of the cone calorimeter tests is the most interesting and the most intense in changes of the measured parameters, the average HRR over a 30 s period of time and HRR_{180s} were investigated (Horváthová & Makovická Osvaldová, 2020). The average HRR over a 30 s period of time were 139.99 kW/m^2, 66.09 kW/m^2 and 142.59 kW/m^2 for laminates I, II and III, respectively. At the time when pHRR is observed, not every part of the material is at their peak burning rate. Some parts of the specimen may not be ignited yet, some may be in the middle of burning, and some of them may be burned out at already. Some studies show that HRR_{180s} may provide a better correlation than the pHRR in the cone calorimeter test (Krasny et al., 2001). At an irradiance level of 25 $kW/m^{2,}$ laminates I and III had the highest values of HRR_{180s} of 117.02 and 119.28 kW/m^2. Much lower value was observed for laminate II (97.79 kW/m^2). All of them were similar to pHRR values. For the irradiance level of 50 kW/m^2, the HRR_{180s} values for laminates I (161.95 kW/m^2) and II (140.45 kW/m^2) were also comparable with their pHRR values. However, the value of HRR_{180s} for laminate III (78.43 kW/m^2) is more than 50% lower than pHRR, due to the fact that after reaching the pHRR, the heat release decreased quickly.

THR describes the total amount of energy released during combustion. Materials with high THR values may contribute to the development of fire (Benzarti & Colin, 2013). THR curves at irradiance levels of 25 kW/m^2 and 50 kW/m^2 are shown in Figure 5 and Figure 6, respectively.

At the irradiance of 25 $kW/m^{2,}$ the course of THR curves of laminates I and III is similar, with a slightly higher THR observed for laminate I (30.1 MJ/m^2) compared to laminate III (29.5 MJ/m^2). Due to the later ignition of laminate II, the THR growth was observed afterwards and reached 24.2 MJ/m^2.

At the irradiance of 50 kW/m^2, the THR values were higher for laminates I and II compared to results taken at lower heat flux. The reduction of THR was observed only for laminate III from 29.5 MJ/m^2 to 27.9 MJ/m^2. The highest THR was observed for laminate I (33.9 MJ/m^2). Lower values of 28.3 MJ/m^2 and 27.9 MJ/m^2 were obtained for laminates II and III. Due to the fact that laminate I and III started burning at a similar time in the first 200s, the course of their THR curves is similar. However, because of the rapid reduction of heat release after the achievement of pHRR, the THR of laminate III is the lowest from all samples.

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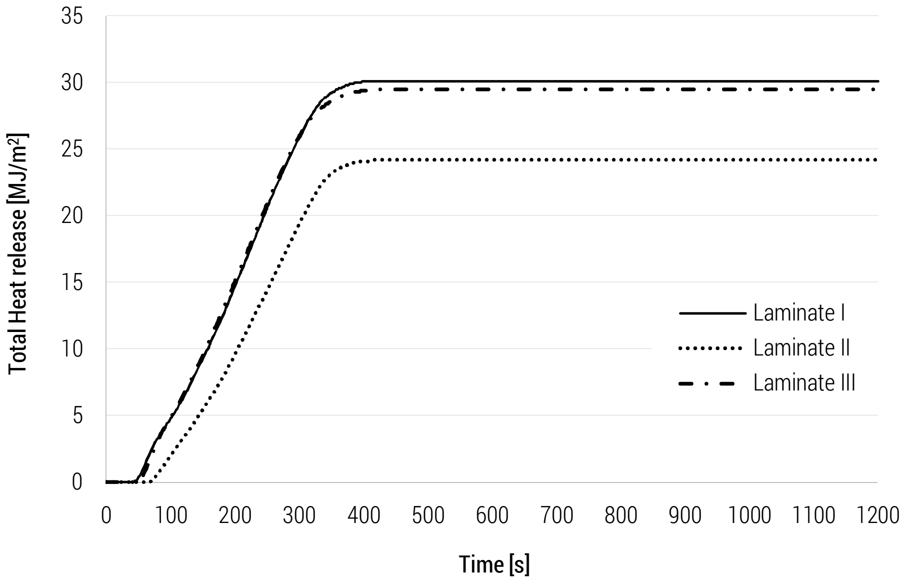

Figure 5. THR curves of laminates under irradiance of 25 kW/m^2

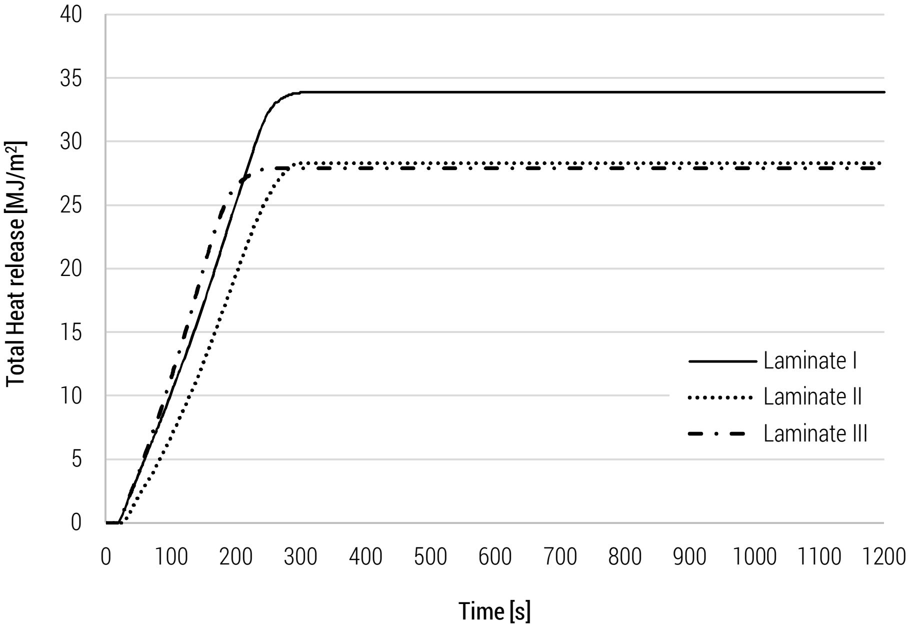

Figure 6. THR curves of laminates under irradiance of 50 kW/m^2

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Smoke release data obtained from the cone calorimeter may provide additional information about the combustion of materials (Sonnier et al., 2019). The TSR at the irradiance of 25 kW/m^2 was the highest for laminate II (123.6 m^2/m^2) with the highest value of Y-CO of 4.978 kg/kg. Slightly lower TSR was observed for laminate I (116.5 m^2/m^2) with the lowest value of Y-CO of 4.359 kg/kg. Laminate III had the lowest TSR of 78.1 m^2/m^{2,} and its Y-CO was 4.577 kg/kg. At the irradiance level of 50 kW/m^{2,} the TSR values of laminates I and II were lower compared to its values at lower heat flux. The reduction of TSR was of 12.88% and 39.16% for laminates I and II, respectively. For laminate, I, the reduction of Y-CO of 17.67% was also observed. A slightly higher value of Y-CO of 1.73% was observed for laminate II, comparing them to the results obtained at lower heat flux. Significant reduction of TSR by 39.95% was observed for laminate III under higher heat flux. The Y-CO was also reduced by 4.96%. The maximum smoke production rate values observed for laminates I, II and III under heat flux of 50 kW/m^2 were 0.0014 m^2/s, 0.0016 m^2/s and 0.0018 m^2/s.

The SEA is defined as a quantity of smoke produced from kg of burned fuel (Barboni et al., 2017). The highest SEA at an irradiance level of 25 kW/m^2 was observed for laminate II (31.8 m^2/kg). Laminate I had a slightly lower SEA (26.4 m^2/kg), whereas laminate III had the lowest value of 18.3 m^2/kg. Accordingly to TSR values, the SEA values for laminates I and II at higher heat flux were lower by 6.82% and 47.48%, respectively. An increase of SEA by 33.33% was observed for laminate III.

Laminate II achieved the highest amount of residual mass (31.33%) at 25 kW/m^2 heat flux. Slightly lower values were observed for laminates I (27.80%) and III (27.96%). At the irradiance level of 50 kW/m^{2,} laminates I and II exhibited higher residual mass, which was higher by 10.55% and 10.93%, respectively. The decrease was only observed for laminate II by 1.39%.

Conclusions

In conclusion, the LCA results showed that electricity contributed most significantly to all impact categories (89% and above of the overall impact). The glass/polyester laminates manufacturing process mainly affects marine aquatic ecotoxicity and accounts for 88.3% of all environmental impact indicators. A contribution analysis showed that the use of electricity dominates; its contribution is over 99% of the MAETP impact category. It becomes clear that MAETP dominates the environmental profile. The reduction of emissions from electricity through total or partial change to electricity from renewable resources may prevent the negative effects of non-renewable

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energy consumption. Significantly lower impact is observed for the freshwater aquatic ecotoxicity, abiotic depletion (fossil fuels), and global warming potentials.

The analysis of heat and smoke release revealed that examined laminates do not meet the requirements of FTP Code Part 10. Under the heat flux of 50 kW/m^2, the TTI for laminates I and III was lower than 20 s, and laminate III had a greater value of 22 s. The average HRR over a 30 s period of time was greater than 60 kW/m^2. The THR was higher than 20 MJ/m^2 for all laminates. Only the criterion of average smoke production rate was achieved with the maximum value of 0.0018 m^2/s for laminate III.

In conclusion, the results showed that formulated laminates do not fulfil the criteria included in FTP Code Part 10 and are not qualified as fire-restricting materials for high-speed craft. Its usage has to be followed by the improvement of flame retardancy, which could be achieved by using flame retardants.

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The contribution of the authors

Conception, A.D. and B.K.; literature review, A.D.; acquisition of data, A.D., D.M. and P.J.; data analysis, A.D.; writing original draft, A.D.; review and editing, A.D., B.K., M.S. and D.M.; preparation of laminates, P.J.; conclusions, A.D.

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