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THE CONCEPT OF USING WIND TURBINE PROPELLERS IN THE CONSTRUCTION OF ACOUSTIC SCREENS AS AN EXAMPLE OF A CIRCULAR ECONOMY MODEL

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ABSTRACT: This paper aims to conceptualise the construction of noise barrier panels from components recovered from used wind turbine propellers. At present, they are mainly waste, but many ideas for their reuse are emerging. Based on previously conducted material tests, the strength of the panels was calculated in accordance with EN 14388. The finite element method and the ANSYS space-claim programme were used to analyse the strength and generate a 3D numerical model of the cracked wind turbine propeller panels. The permissible values given in the standard were compared with those obtained for the deflection of the component.

KEYWORDS: GFRP turbine propellers, acoustic screens, flexural behaviour, FEM analysis

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Introduction

One strategy for implementing sustainable development, which has gained popularity among economists, policymakers, and businesspeople, is the circular economy. Although there are many different circular economy concepts, they all describe a new way of adding value – and ultimately prosperity – by extending the life of products and moving waste from the end of the supply chain to the beginning – effectively using resources more than once. The way things are made now involves taking natural resources from the environment, transforming them into new things, and then discarding those new things back into the environment. It is a sequential process with a start and finish. Limited resources in this system will eventually exhaust themselves. Waste builds up, resulting in contamination or high disposal costs. Additionally, production procedures are frequently ineffective, which results in additional resource waste. A circular economy, however, uses materials from previous products to create new ones. Everything is recycled whenever possible, produced again, or, as a last resort, turned into raw materials or used as an energy source.

Governments are promoting the adoption of circular economy principles that would result in greater resource efficiency and less waste, and in some cases, requiring it. The creation of goods that require fewer virgin resources, last longer, and can be repaired, recycled, or repurposed at the end of their useful lives are the fundamental tenets of the circular economy.

The construction industry generates the greatest environmental burden. One of the most essential components of concrete is Portland cement, which is one of our most popular building materials. The production of cement produces about the same amount of carbon dioxide as one kilogram of cement. Additionally, the amount of concrete used worldwide is increasing quickly each year in tandem with population growth, making it crucial to take advantage of circularity opportunities in the construction sector in order to promote economic and sustainable development. Furthermore, the environmental effects of the construction industry do not end once a project is finished. The operating and maintenance costs of a built structure over its anticipated lifespan of 50 to 100 years continue to be a burden on the environment. Our buildings account for over 40% of primary energy consumption, and they also produce a significant amount of harmful emissions. A similar amount of harmful substances are also released into the atmosphere during demolition, which occurs at the end of the life cycle.

Concrete is the most common material used to create soundproof screens. Concrete noise barriers are frequently distinguished by high acoustic insulation values (Nowoświat et al., 2018). Aside from cost, the advantages of concrete acoustic screens include durability and low sensitivity to environmental factors. Although they don't need to be cleaned or maintained, their appearance is typically not eye-catching. For very long screens, changing the texture and colour of the screen keeps drivers from becoming bored or monotonous. Climbing plants may overgrow porous concrete screens (made, for instance, of wood chips), greatly enhancing their appearance. Expanded concrete acoustic screens have the ability to reflect and absorb sound waves. The composition of the materials used to make screens and the technology used in their production ensure that they have excellent functional qualities. Concrete prefabricated and steel columns serve as the screen's load-bearing element. Between the columns is a sound-absorbing panel made of an expanded clay sound-absorbing element technologically connected to a reinforced concrete slab.

Where good visibility is required, transparent plastics are used to create acoustic screens. High surface hardness, acoustic insulation, UV resistance, high transparency, smoothness, and processing ease are some of this material's distinguishing qualities (Forssen et al., 2019). Although polymeric materials have many advantages, they can also cause waste or pollution, which has undesirable effects. Over the past 50 years, the use of plastics has multiplied 20-fold. Plastics are used for packaging to a degree of about 40%. By 2050, 318 million tonnes of plastic packaging are anticipated to be produced annually, more than quadrupling from current levels. Despite their versatility, plastics are a very wasteful material in the way we use them. Earth's natural resources, oil and gas, are used to create plastic products, many of which are disposable after a single use. Billions of dollars' worth of plastic waste that weighs millions of tonnes ends up in landfills, is burned, or gets released into the atmosphere. Growing plastic waste harms marine ecosystems, biodiversity, and perhaps even human health.

Recycling of turbine blades

A significant source of clean, affordable, and emission-free electricity is wind energy. Wind turbines use the kinetic energy of the wind to generate electricity by converting it to mechanical energy. This type of electricity generation is regarded as renewable energy because it is self-renewing and doesn't emit pollutants into the atmosphere. To be truly "green" an energy source must have zero or almost zero environmental impact in terms of waste and emissions over the course of its entire life cycle. It is also crucial to consider the environmental impact at the end of its useful life. Therefore, it's crucial to recycle or reuse old wind turbine blades after they've served their purpose.

Since the first commercial wind turbines went online in the middle to late 1990s, the question of what happens to their waste materials as they approach the end of their operational lives and decommissioning has arisen. Some people believe that wind turbines are bad for the environment because some of their parts, like their blades, cannot be recycled. Despite the fact that some cannot be recycled, manufacturers and operators are making great efforts to make them as sustainable as possible by finding ways to recycle, reuse, or rebuild them using recyclable materials in the future. Wind farm turbine blades are incredibly challenging to recycle. The majority of the materials used to make the blades is fibreglass. An onshore wind turbine's typical blade measures about 50 metres in length. However, there is a growing trend for taller turbines, which are frequently found offshore at sea and have blade spans as long as 80–90.

Fibreglass can't always be recycled. It is made of a composite of very fine strands of plastic and glass, making it non-biodegradable and extremely challenging to process at the point of recycling. Instead, it's typically burned or dumped as waste in landfills. Not all first-generation commercial blades are, however, destined for landfills, even though the majority of them are being treated as waste. Their raw materials can be recycled in a variety of creative ways to be turned into new building materials or completely repurposed for use in different types of structures. The issue of how to recycle and reuse wind turbine blades has been addressed through a number of initiatives, ensuring the long-term viability of this form of energy production (Mishnaevsky, 2021). He indicates three types of recycling blades: (1) primary recycling – reuse, and refurbishment in both wind turbines and other structures; (2) secondary recycling in mechanical processing of the material; (3) thermal or chemical recovery.

Examples of the first type of recyclingare bike sheds in Denmark (Figure 1), noise barriers for highways in the US, "glamping pods" across festival sites in Europe, or components of civil engineering projects, such as pedestrian footbridges in Ireland. They are also finding ways to repurpose turbine blades as complete structural elements.

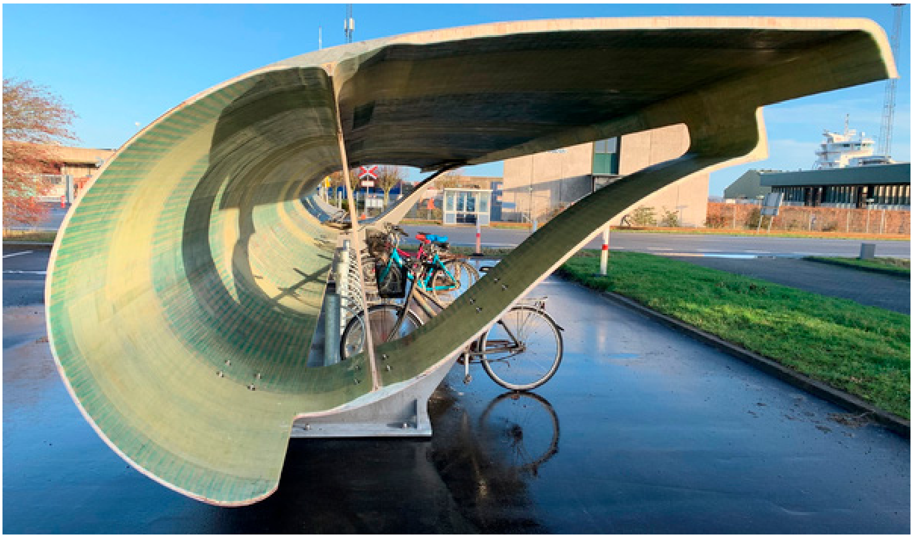

Figure 1. Bike sheds

Source: Awesome Inventions, 2023.

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However, the materials that go into making wind turbines are chosen for their resilience to hurricane-force winds. While this durability is helpful when operating wind turbines, it frequently prevents blades from being crushed, recycled, or used for another purpose after their useful lives have expired. In addition to the material's difficulty in decomposing, the turbine blades' length also makes it challenging to dispose of these parts because big rigs can typically only transport one blade at a time. Although the majority of wind turbine blades can last up to 20-25 years, the majority of blades are removed after 10 years so that larger and more powerful designs can be installed in their place. Thousands of used turbine blades are piling up in landfills around the world because they are frequently made of materials that cannot be recycled or reused (Figure 2).

Figure 2. Discarded wind turbine blades fill thirty acres on the west side of Sweetwater

Source: Doomberg, 2023.

The blades can be broken into a few pieces on site during a decommissioning or repowering process, but transporting the pieces for recycling or disposal is still challenging and expensive. And in order to cut the incredibly strong blades, large machinery is needed, such as wire saws mounted on vehicles or diamond-wire saws similar to those found in quarries. The majority of blades that reach their end of useful life are either being stored in various locations or being sent to landfills because there are currently so few options for recycling the blades.

Pyrolysis is a technique used to recycle materials, in which high heat decomposes the composite's organic elements in the absence of oxygen and separates them from the inorganic glass fibre. Through this process, organic materials are transformed back into unprocessed hydrocarbons that can be used to create energy and are referred to as syngas and pyrolysis oil. This makes the process overall beneficial. After being separated, the recycled glass fibre can be cleaned and used again to make new products (Figure 3) (Giorgini et al., 2016).

Figure 3. Pure recycled glass fibre from retired wind turbine blades

Source: Carbon Rivers, 2023.

Global Fibreglass Solutions (GFS) has converted the fibreglass composites derived from old turbine blades into small pellets known as EcoPoly (GFS, 2023). EcoPoly pellets can be used as waterproof boards for construction or as injectable plastics. The pellets available for purchase are thermoplastic fibreglass pellets that can also be widely used in injection mould and extrusion manufacturing processes. EcoPoly Pellets are made to order for customers based on the specifications of their own manufacturing process.

Acoustic screens

An acoustic screen is an artificial barrier that prevents the propagation of sound waves between the sound source and the area protected against noise (Kotzen & English, 2009). Sound waves are partially absorbed, reflected, and deflected at the edge of obstacles they encounter. The area protected from the negative effects of road noise located behind the screen is the so-called acoustic shadow area. The effectiveness of the screen depends primarily on what part of the noise will be absorbed by the screen and what part of the noise will be transferred to the acoustic shadow zone due to wave refraction (diffraction).

Developing acoustic screens for road route communication necessitates an extensive strategy. Apart from the efficiency of the screen as an anti-noise device, many more variables pertaining to the road's characteristics, coordination with road infrastructure devices, and resilience to harsh environments (rural, industrial, and urbanised areas) should be considered. When choosing a screen, aesthetic considerations, local conditions, and environmental protection should all be considered. Materials like concrete, steel, glass, ceramics, plastics, and wood can all be used to create screens. Acoustic screens can be constructed as hills or embankments encircled by vegetation in places with low levels of urbanisation. However, the most common type of screens are still vertical partitions with a height and structure that guarantee proper conditions in the acoustic shadow region. Prefabricated concrete acoustic panels are relatively inexpensive to create screens out of, and they require very little maintenance. Screens made of plastic, metal, or transparency typically have higher construction and maintenance costs.

There are several factors that determine how effective acoustic screens are. These include the screen's height, width, and placement in relation to the noise source, in addition to its construction and texture. Selecting and placing sound-absorbing screens can be made much easier by being aware of the basic principles governing their operation. The phenomenon known as "sound wave absorption" refers to the energy waves being absorbed by the screen material. Here, the structure's porosity is crucial; the more, the better the damping. In a competition like this, elements composed of bulky, relatively thick materials will obviously be more effective. The frequency of sound waves is also significant because higher frequencies attenuate sound waves more successfully. It follows that high-frequency noise sources will produce more of an effect on sound-dampening screens than low-frequency noise sources. In turn, a sound wave's reflection results in a direction change in the wave's propagation. When we picture a smooth screen surface, it is essentially a mirror reflection. This definition is very clear and easy to understand, but it can get a little confusing if you keep bringing up the frequency of sounds the screen is meant to block out and assume that the screen has a texture. Specular reflection only happens in this situation when the surface irregularities are significantly larger than the wavelength. In terms of noise reduction, scattering – which happens when these two parameters are near to one another – is far more effective than regular specular reflection. In this instance, the direction of the reflected sound waves starts to seem random, which lowers their level even more. Once more, we can choose the acoustic screen's texture to disperse the best sounds, which, in this instance, make up the majority of the noise we wish to block out. Here are some examples so you can see what quantities we are talking about. Twenty Hz sound waves in the air have a length of 17 m, while twenty kHz sound waves have a length of 1.7 cm. These are the approximate bounds of sound waves. The majority of the time sounds with a frequency of about 1000 Hz, or a wavelength, dominate traffic noise.

Sound absorptive treatment is generally a good approach to stop sound reflection issues. Prior to the sound wave being reflected from a noise barrier, the sound absorptive treatment will absorb sound energy. In order to lessen annoyance for the nearby residents, a significant portion of the energy from the image sources is added to the total energy, and a smaller amount of sound energy is reflected from highway noise barriers (Chua, 2004). The absorption coefficient α, is used to rate how well sound absorbs. The percentage of sound energy absorbed relative to the energy striking the surface is known as the frequency-dependent absorption coefficient. The coefficient α, which has a theoretical range of 0 to 1, is highly dependent on frequency. When $\alpha = 0$, the material reflects all incident sound energy and does not absorb any sound. When $\alpha = 1$, no sound energy is reflected from the material and all sound energy is absorbed.

The NRC rates fibreglass insulation typically in the range of 0.90 to 0.95. With such a high rating, fibreglass is a great option for reducing noise in a variety of settings, including offices, commercial buildings, private homes, schools, and more. The glass fibre content in acoustic materials both lowers sound transmission and increases impact sound insulation. Additionally, the glass fibre mats in the composite elements stop pieces from breaking, which could happen, say, if a car runs into an acoustic wall. When composite materials are used to create acoustic screens, they guarantee a high degree of self-cleaning of the boards due to atmospheric precipitation, light structure, extreme resistance to weather and ageing, ease of forming and processing, and the potential for recycling. Furthermore, a structure that actively disperses sound and lowers its level in the direction of reflection is produced by constructing an acoustic screen with a curved surface using composite elements made from cutting wind turbine blades. Consequently, it makes sense to build screens out of materials that are not only weather-resistant but also have a high degree of dissipative surface area.

Geometry and construction of acoustic screen

The case study that is being presented includes an acoustic screen that is made up of steel columns set in concrete piles, a ground beam, and acoustic panels. The components of a screen are as follows: an acoustic panel composed of composite elements measuring 3000 mm by 300 mm by 30 mm in length, width, and thickness and aluminium side frames with a 100x50x5 mm C-section. The 3000x3000 mm examined acoustic panel is made up of 10 composite pieces that are joined together with 3M VHB tapes. Figure 4 depicts the geometry and cross-section of the road noise barriers, respectively.

European standards (EN 1794-1:2003; EN 1794-2:2003) provide requirements for the design of acoustic screens as independent load-bearing structures. Eurocode specifies the maximum horizontal displacements allowed for individual screen elements.

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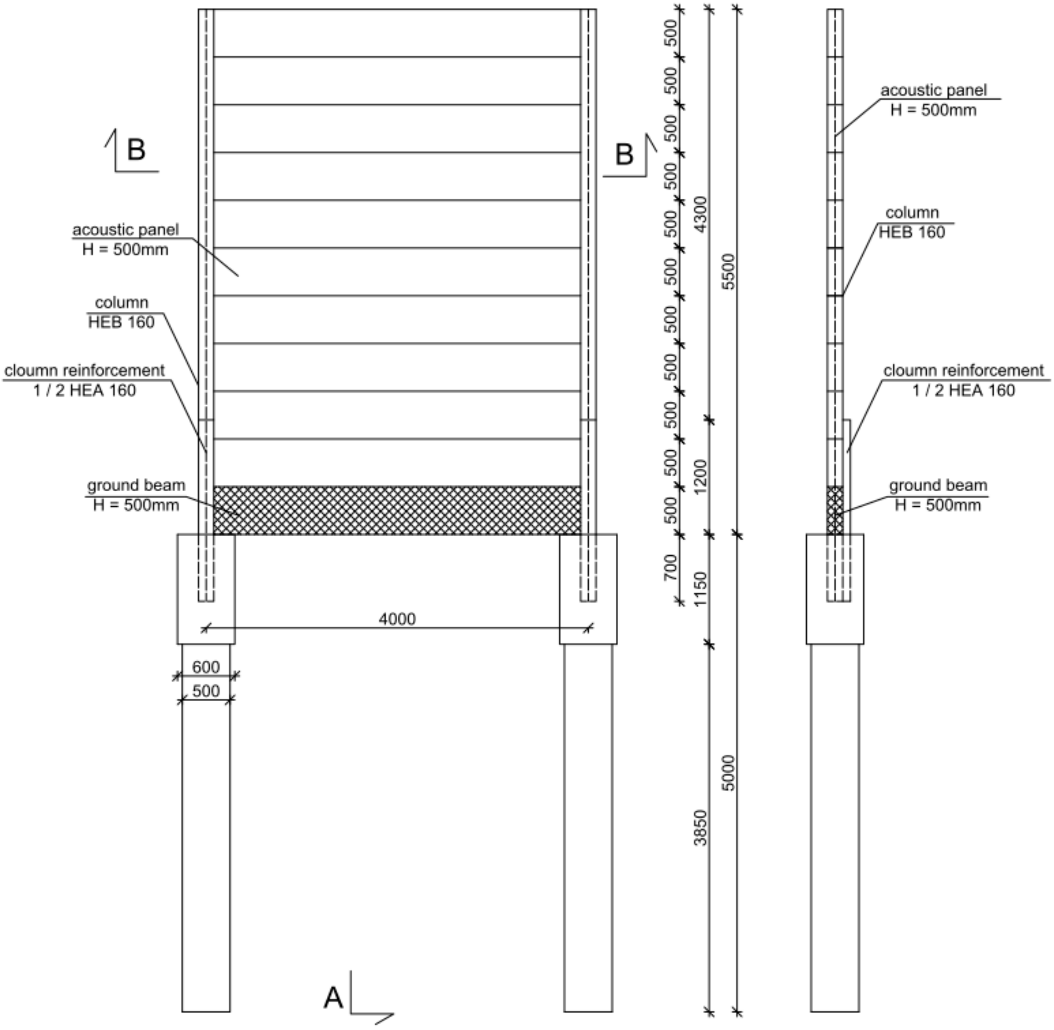


Figure 4. Geometry of the road noise barriers

Furthermore, it's imperative to stop the formation of permanent deformation, the non-reversible displacement of acoustic elements, the separation of individual panels, and the detachment from supports or fixings (EN 1794-1:2003). The permissible elastic deflection for wind load or load caused by car traffic is presented in Table 1.

The research led to developing an acoustic panel prototype of a glass fibre-reinforced composite for use in screen construction. We propose the panel, measuring 3000 mm in width and 3000 mm in height, composed of recycled wind turbine propellers. The panel that is being presented has been engineered to achieve a high sound dispersion coefficient while adhering to mechanical specifications that allow it to be used in standard road noise barrier structures. Regardless of the effect of sound dispersion, the screen's acoustic absorption is shaped by its construction of sandwich elements, in which a balsa wood fills between two layers of the composite. The structure is double-sided and can be used interchangeably, allowing various configurations in the screen structure.

Table 1. Permissible deflection (EN 1794-2:2003)

Type of load	Elastic deflection		Non-reversible deflection	
	Structural element	Acoustic element	Structural element	Acoustic element
Wind		50 mm		
Load caused by car traffic		50 mm		
Dead weight	not specified	not specified	not specified	
Snow	not specified	not specified	not specified	not specified

where: L_S – the length of the structural element, in mm, L_A – the largest length of the acoustic element, in mm, h – total height of the acoustic element, in mm.

Composite elements of acoustic panel

The acoustic panel elements are boards cut from a wind turbine propeller, 30 m long and 1.12 m to 2.365 m high (Figure 5). A fragment of the propeller created after cutting off the end of the propeller and the hub (beginning) of the propeller (Figure 6) was used to cut out the panel elements, which were 3000 mm long and 300 mm wide. A wind turbine blade consists of both solid (solid) glass laminates and sandwich laminates, in which the outer glass cladding is separated by a balsa wood core. As part of the research, a numerical model of a sound-absorbing panel with an innovative spatial structure was developed, made of curved composite elements, which are sections of propellers connected together with an acrylic sealing tape (single-sided adhesive) Extreme Sealing Tape.

The view of sections taken from wind turbine propellers, from which the elements constituting the basis for the acoustic panel were cut out, is shown in Figure 7, while Figure 8 shows cross-sections of propellers.

Figure 5. Wind turbine propeller segments with a total length of approximately 30 m

Source: Road and Bridge Department, 2020.

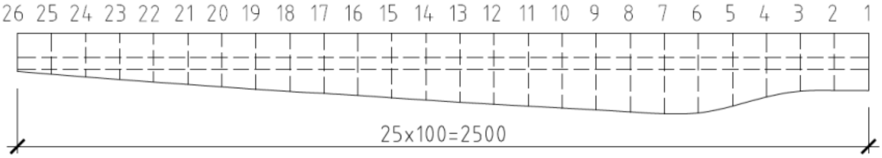


Figure 6. Propeller dimensions after cutting off the end of the propeller and the hub

Source: Road and Bridge Department, 2020.

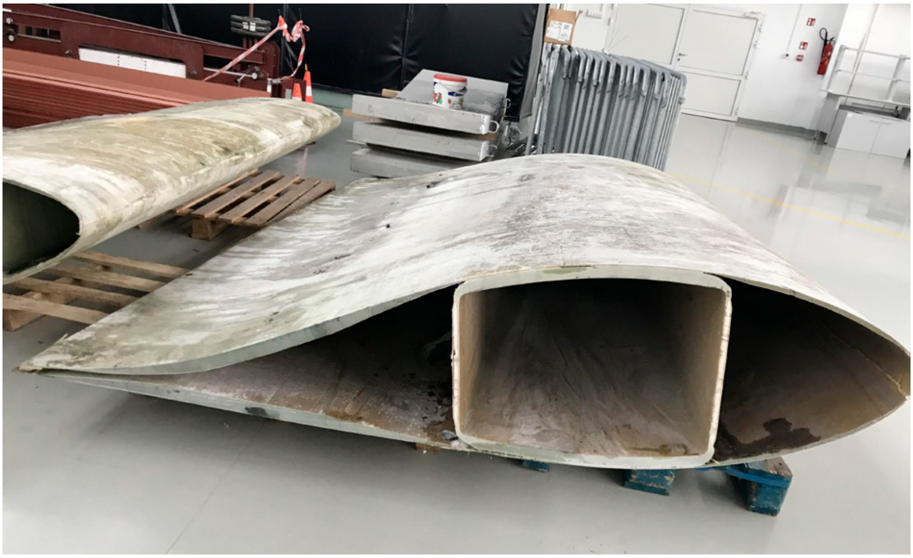


Figure 7. View of sections taken from wind turbine propellers

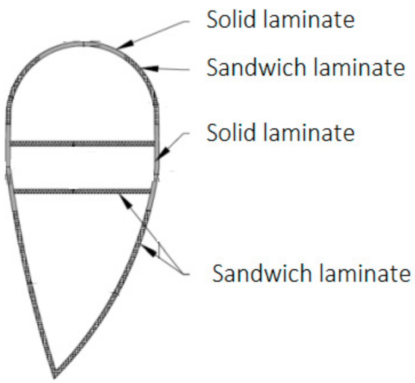


Figure 8. Cross-sections of propellers

A 3D model of a fragment of a windmill propeller was created in the ANSYS SpaceClaim program, shown in Figure 9. This fragment covers the first 17 meters of the beam's length, starting from the point of connection with the propeller axis. The model has been divided into 3-meter sections from which elements will be cut to create the acoustic screen field. These fragments will be placed in a frame made of C 100×50×5 mm aluminium catheters, attached to steel poles made of 160 I-beams.

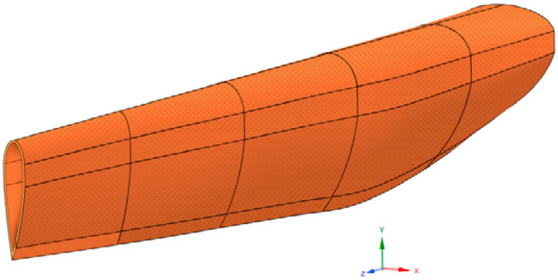


Figure 9. 3D model of a fragment of a windmill propeller

Then, from each segment, composite elements 300 mm wide were cut to use as parts of acoustic panels (Figure 10).

For the purpose of FEM strength analysis, the cut segments were discretised with a spatial mesh and divided into solid elements with a side length of approximately 5 cm (Figure 11). In order to reproduce the mounting conditions in the acoustic screen panel, all degrees of freedom of the edges of the shorter sides of the elements have been blocked. The laminate D was modelled in the ANSYS ACP module, taking into account the type of laminate and the properties of balsa wood constituting the core layer of the laminate.

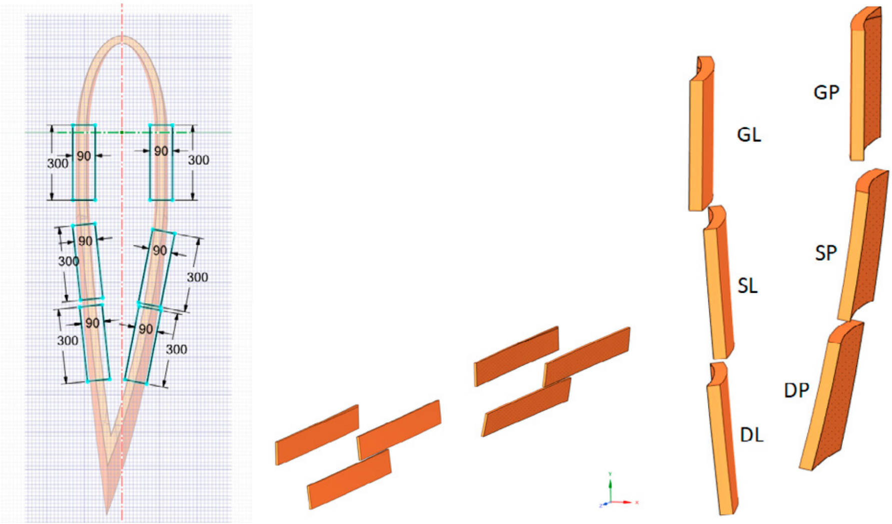


Figure 10. Components of panels cut from windmill blades: GL – left side solid element, GP – right side solid element, SL(DL) – left side sandwich element, SP(DP) – right side sandwich element

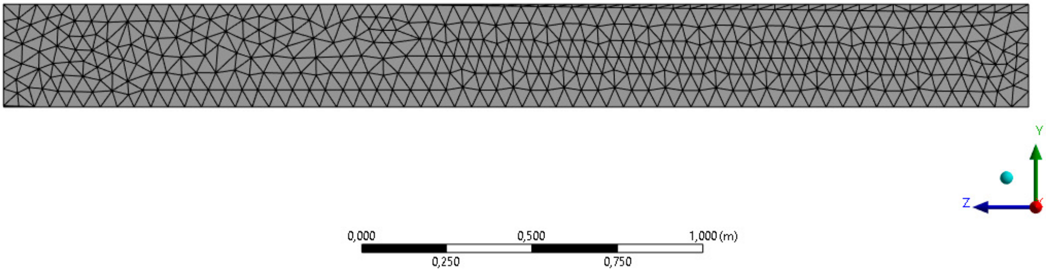
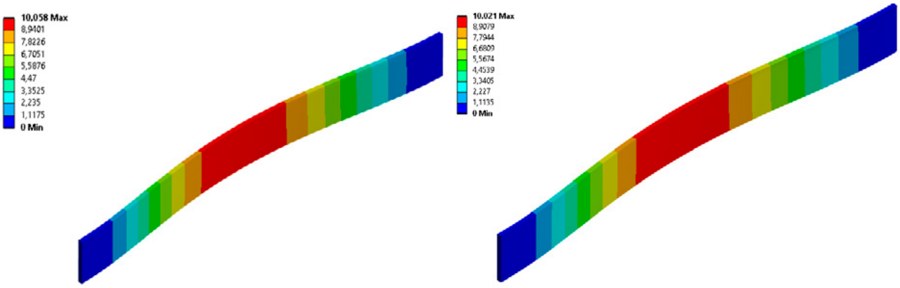


Figure 11. Method of discretisation of the GP element

Loads related to wind pressure and caused by car traffic were applied to the elements, forming an acoustic panel. The obtained element deflection values were compared to the acceptable values listed in the standard EN 1794-2:2003 (Figure 12). The maximum deflection of solid composite elements GP and GL cut from the propeller of a wind power plant was 10.1 mm, and the deflection of sandwich composite elements SP and SGL was 0,02 mm, which is much smaller than the permissible deflection of 3000/150 = 20 mm.

GP element GL element



SP element SL element

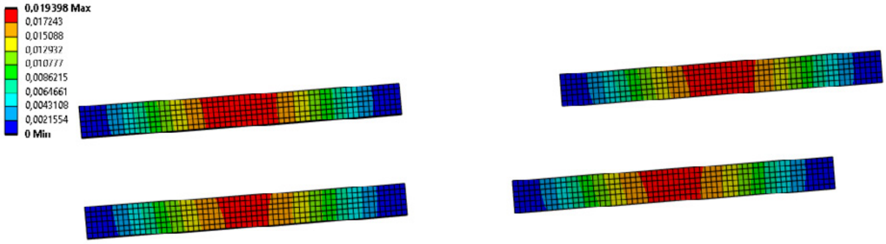


Figure 12. Map of deflection values of the GP and GL solid elements and SP and SL sandwich elements in mm

Environmental impact of acoustic screens

The material-intensive nature of building sound barriers raises concerns about their overall environmental impact. Currently, the most commonly used noise barriers are made of concrete, metal (metal plates filled with a sound-absorbing material such as glass wool), tempered glass, acrylic or wood. A substitute for these virgin raw materials can be a composite recovered from wind turbine blades, the reuse of which requires much less effort than recycling and can bring greater environmental benefits (Nagle et al., 2020).

Assessing the environmental impact of sound barriers using the LCA method takes into account the impact of a product's interaction with the environment at every stage of its life, from the production of raw materials to the point of scrapping or recycling. This impact can be reduced to the impact of the material from which the barriers are made. However, this approach does not consider the processes directly related to the barrier's production, transportation and installation. These values can be a starting point for assessing the potential for reducing the environmental impact of sound barriers made from composite material recovered from wind turbine blades, which is the subject of this article. Table 2 shows the embodied values (cradle-to-gate range) of energy consumption and greenhouse gas emissions for one slab of finished barrier made from each material (Xie et al., 2022).

Table 2. Embodied energy and embodied carbon content of other sound barrier materials

Material Type	Embodied Energy [MJ/kg]	Embodied Carbon [kg$CO_{2eq.}$/kg]
Aluminium	155,0	6,67
Acrylic board	90,67	-
Tempered glass	23,50	1,67
Galvanised steel	22,60	3,03
Mineral wool	16,60	1,20
Wood	16,00	0,815
Concrete	0,82	0,15

Source: Xie et al., 2022.

It should be noted that since the composite material for sound barrier production extracted from wind turbine blades is a reusable waste, it is a substitute for virgin raw materials. The values of environmental impacts resulting from the substitution of virgin materials for waste should be taken as negative and eventually be subtracted from the total environmental impact of the resulting sound barrier, taking into account such processes as cutting the wind turbine blades, making the steel poles, transporting and installing the sound barrier. The LCA method can be successfully used in this case to measure the benefits gained from material substitution (Turconi et al., 2011), which the authors intend to analyse at a further research stage.

Conclusions

The research aims to use elements from wind turbine propellers to make acoustic panels that will be used to build acoustic screens. As preliminary calculations showed, the 25 m long and approximately 1.5 tonne propeller will allow the construction of approximately 40 square meters of the sound barrier. The essence of the proposed solution will be to make sound-absorbing panels from propeller sections, which will minimise the technical operations necessary to make sound-absorbing panels and thus significantly reduce the environmental costs of the project. First, a conceptual analysis was carried out on the possibility of using elements from turbine blades to make acoustic screen panels. It allowed the development of a method of matching elements from wind propellers to create a unified soundproof panel. As part of the research, a numerical model of a sound-absorbing panel with an innovative spatial structure was developed, made of curved composite elements, which are sections of propellers connected with an acrylic sealing tape (single-sided adhesive) Extreme Sealing Tape. The use of composite materials with better acoustic properties and, at the same time, high durability and resistance to chemical agents will significantly increase the service life compared to such structures made of steel sheets, which are susceptible to corrosion hazards. Strength calculations of the panels were made in accordance with the requirements of the EN 14388:15 standard on the basis of previously conducted material tests. They were carried out in terms of strength, durability and safety of use of the designed panels and included the strength properties specified in the Table PN-EN 14388 standard in the form of panel resistance to loads related to its own weight, wind load and car traffic. Strength analysis was done using the finite element method and the ANSYS Space-claim programme to create a 3D numerical model of the panels of a fractured windmill propeller. The values obtained for element deflection were compared to the acceptable values found in the standard. The maximum deflection of sandwich composite elements SP and SGL and solid composite elements GP and GL cut from a wind power plant's propeller was 0.02 mm, and the maximum deflection of both types of elements was 10.1 mm, which is significantly less than the allowed deflection of 3000/150 = 20 mm.

When the amount of deformation of the acoustic panel was compared to the allowable values, it was discovered that, in terms of manufacturing technology and strength, using composite elements cut from wind turbine blades was a good option for producing acoustic panels for road screens. In addition, using wind turbine waste as a raw material for constructing noise barriers can contribute to reducing environmental impacts.

The contribution of the authors

Conception, M.B.; literature review, M.B. and B.S.; formal analysis, F.B. and K.D., editing, M.B. and B.S.; conclusions, M.B., F.B., K.D. and B.S.

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KONCEPCJA WYKORZYSTANIA ŚMIGIEŁ TURBIN WIATROWYCH DO BUDOWY EKRANÓW AKUSTYCZNYCH JAKO PRZYKŁAD MODELU GOSPODARKI O OBIEGU ZAMKNIĘTYM

STRESZCZENIE: Celem artykułu jest koncepcja budowy paneli ekranów akustycznych z elementów odzyskanych ze zużytych śmigieł turbin wiatrowych. Obecnie stanowią one głównie odpady, lecz pojawia się wiele pomysłów ich powtórnego wykorzystania. Na podstawie przeprowadzonych wcześniej badań materiałowych obliczono wytrzymałość paneli zgodnie z normą PN-EN 14388. Do analizy wytrzymałości i wygenerowania trójwymiarowego modelu numerycznego pękniętych paneli śmigła wiatraka wykorzystano metodę elementów skończonych oraz program ANSYS Space-claim. Dopuszczalne wartości podane w normie zestawiono z wartościami uzyskanymi dla ugięcia elementu.

SŁOWA KLUCZOWE: łopatki turbin z GFRP, ekrany akustyczne, zachowanie przy zginaniu, analiza MES

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