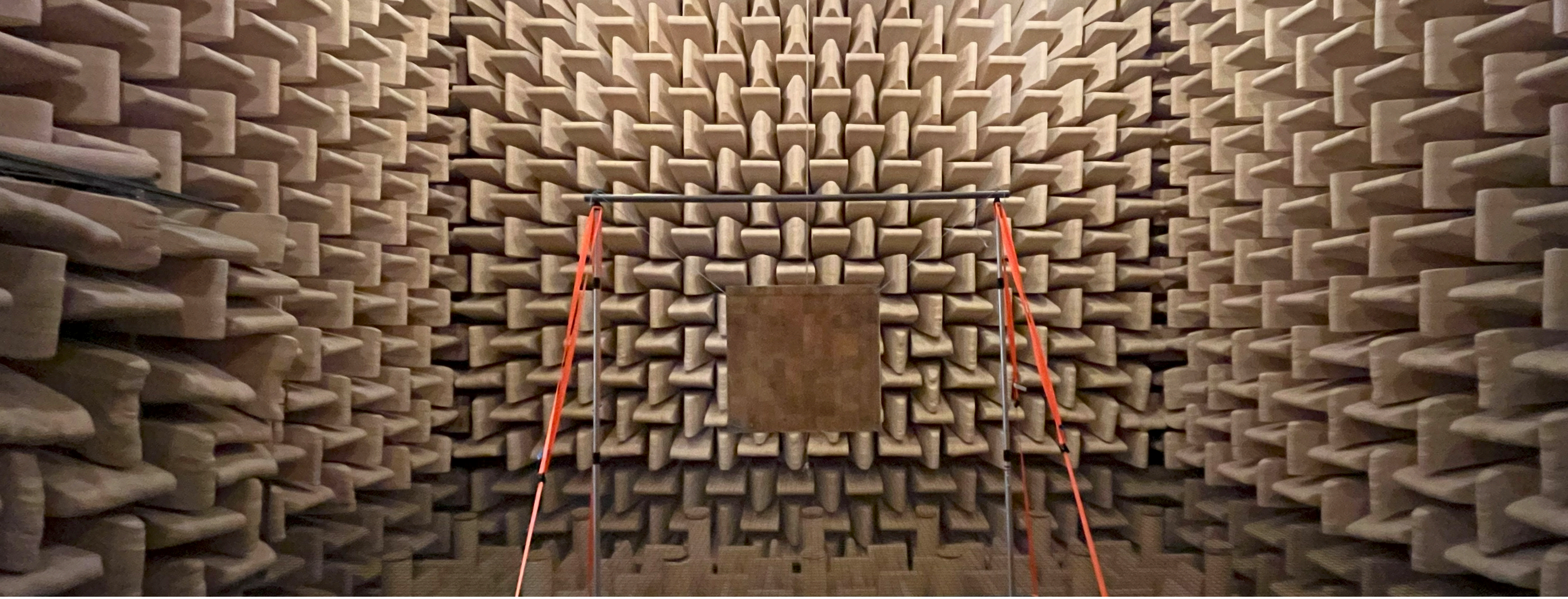

Finding applications for end-of-life wind turbine blade materials based on their acoustic properties

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MASTER GRADUATION THESIS
26-07-2024

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ABSTRACT

Current wind turbine blades are made from a material that is difficult to recycle, while a lot of them are being decommissioned. A large influx of high-performance and high embodied energy wind turbine waste material (WTBM) is forming. Next to structural applications, very few novel applications that make proper use of the excellent material properties of decommissioned WTBM are known.

To identify novel applications for WTBM sourced from decommissioned wind turbines a focus on the acoustic properties of WTBM was taken. Various strategies including a variation on material driven design, i.e. circular application through selection strategies (CATSS), were used to identify applications. For that, relevant acoustic WTBM properties were determined to properly identify a knowledge gap. To evaluate the applications identified through CATSS, experiments were set up in the anechoic chamber of the Applied Sciences faculty of the Delft Technical University. The data generated from these experiments, together with the knowledge gained during earlier parts of the project were used for concept ideation of an acoustic application. Sitka Spruce, a natural tone wood used for making tone boards in acoustic instruments, has been found to be the most acoustically similar to WTBM. Based on that, various applications including a distributed mode loudspeaker (DML) line array, acoustic instruments and a resonating acoustic amplifier (RAA) have been identified and evaluated. An application based on replacing tone wood in a resonating acoustic amplifier (RAA) was chosen to embody through a functional prototype. The performance of this RAA prototype showed that WTBM has potential to replace tone woods in acoustic applications; however, more research is needed to identify all the advantages and limitations of such a replacement.

LIST OF ACRONYMS AND ABBREVIATIONS

AV	Acoustic velocity
CATSS	Circular applications through selection strategies
CFRP	Carbon fiber reinforced plastic
DML	Distributed mode loudspeaker
EPS	Expanded polystyrene foam
EU	European Union
GF	Glass fiber
GFRP	Glass fiber reinforced plastic
GW	Giga Watt
GWh	Giga Watt hours
IDE	Industrial Design and Engineering
MDD	Material driven design
PET	Polyethylene terephthalate
RAA	Resonating acoustic amplifier
SPL	Sound pressure level
TL	Transmission loss
TW	Tera Watt
TWh	Tera Watt hours
WTB	Wind turbine blade
WTBM	Wind turbine blade material

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INTRODUCTION

Energy harnessed from the wind is not a new technology, which any Dutch resident will proudly affirm. Windmills have been around for several millennia, with wind powered sail boats being older still. In modern times, as early as the 1980s, wind turbines as we know them today were first introduced in the United States, but global adoption of the technology did not take off until halfway in the 1990s (Kaldellis & Zafirakis, 2011). Renewable energy is currently more relevant than ever, with many nations across the world setting ambitious goals for carbon emissions through the Paris agreement in 2015 (United Nations, n.d.-b). To achieve this goal, our energy production and consumption need a complete overhaul, where a shift towards renewable and carbon neutral technologies is required. One of the pillars of current renewable energy production is wind energy. According to Yolcan (2023), the global amount of renewable energy produced in 2021 from wind was 1861,9 TWh, amounting to roughly half of the energy produced by all renewable sources combined. Next to this, as can be seen in Figure 1, in 2023 roughly a quarter of the total electricity production in The Netherlands came from on- and offshore wind turbines (CBS, 2024). Wind energy output is continuously growing worldwide, with many offshore wind parks being added.

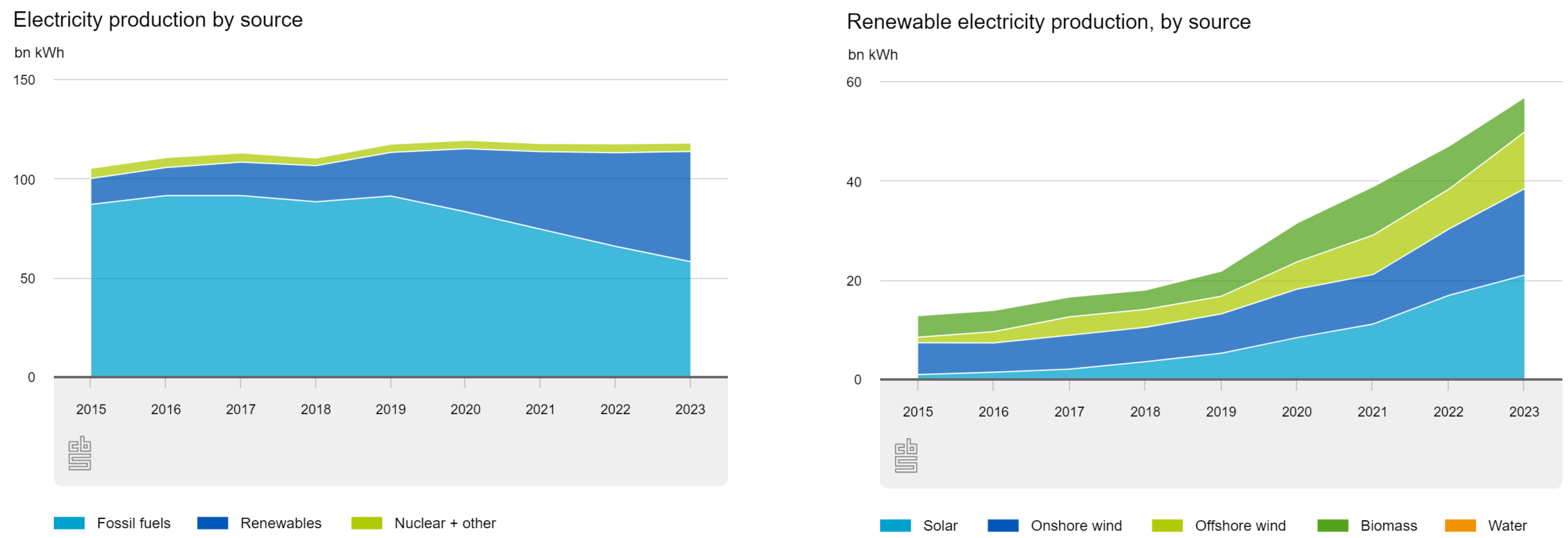


Figure 1: Above: the total energy production per source in the Netherlands. Below: the division of renewable energy production in the Netherlands (CBS, 2024).

RESEARCH GOAL

Identify acoustic applications for wind turbine blade materials (WTBM) originating from decommissioned wind turbine blades (WTBs) that make use of its high-performance properties.

RESEARCH QUESTIONS

1: What are the material properties of DWBM?

2: What are suitable applications for repurposing DWBM?

GOALS

To ensure that the identified application(s) for DWBM that are found have merit it (they) must:

1. Be based on at least one specific material property that WTBM excels at.
2. Perform as well as or better than the current material(s) used in the application.
3. Be feasible, viable and desirable enough to justify its existence.
4. Have an acoustic function.
5. Showcase a novel way of using WTBM.

NICE-TO-HAVES

The identified application is of enlarged value if it:

1. Replaces a (virgin) material with high embodied energy costs.
2. Requires little reprocessing of the original material.
3. Has a “wow-factor” that helps call attention to the WTBM waste problem.

For a complete description of the initial project brief, see Appendix A.

PROBLEM DEFINITION

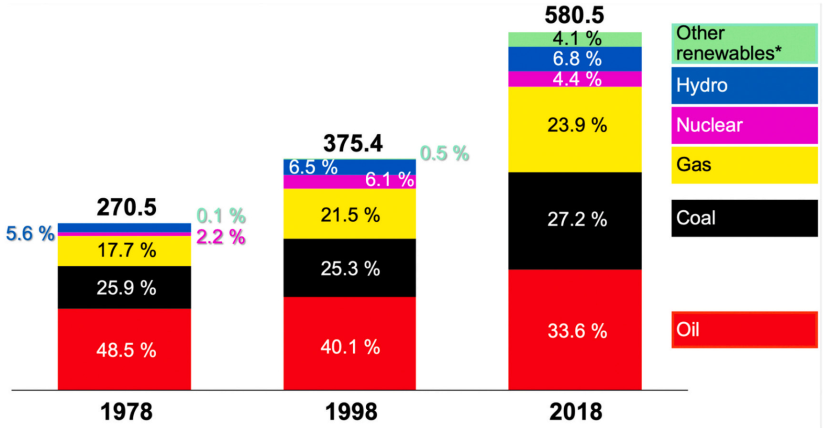


Figure 2: Total energy consumption of the world between 1978 and 2018 (Kober et al., 2020).
* Other renewables are wind, solar, geothermal and bio-energies.

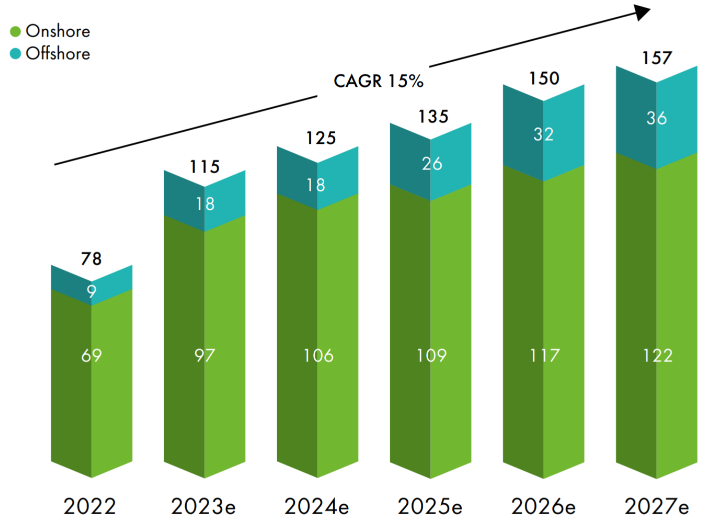


Figure 3: Projected new wind turbine installations between 2022 and 2027 (GWEC, 2023).

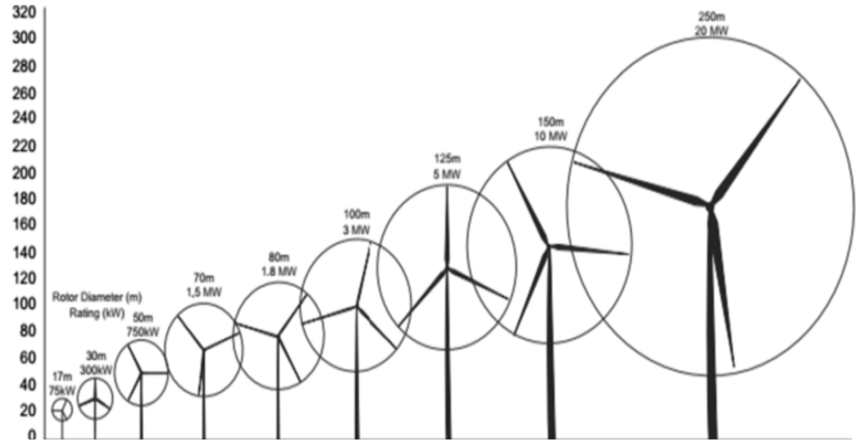


Figure 4: Past WT diameters compared to current and future sizes (Bashir, 2021).

In the first quarter of 2012, the cumulative growth of global wind turbine output was close to 19 percent, totaling 282,5 GW (Sawyer et al., 2013). If all the wind turbines in 2012 ran for one hour, they would produce 282,5 GWh of energy. According to carbon collective, a typical average US household consumes around 0,01G Wh per year (Stein, 2024). As of November 2022, the global population has exceeded eight billion (United Nations, n.d.). To power all households for one year, the global energy output of all wind turbines in 2012 would need to be stored in a giant battery for 70 weeks, assuming the wind constantly blows everywhere day and night, and assuming all households on earth were typically American. Luckily, for more reasons than one, not all households are typically American, and the earth has much more energy production capacity than solely wind turbines. The global energy production in 2018 was 580 exajoules, or 161111111 GWh (Kober et al., 2020). When looking at global energy production between 1978 and 2018, only a few percent of the total energy is produced by wind turbines (as shown in Figure 2).

According to the Global Wind Energy Council (2023), the global wind turbine output will exceed the 1 TW mark by 2027, with Figure 3 showing new installations between 2022 and 2027 totaling 680 GW. The end of this growth is not yet in sight, with BloombergNEF suggesting that by 2030 the global wind power will have almost doubled to 2 TW (New Energy Outlook 2024, 2024). Paradoxically, wind turbines are both a part of the solution to the need for renewable energy and emission reduction, yet also a major source of waste and emissions itself. Wind turbines last for an average of 20 to 25 years before they are scrapped and replaced, blades manufactured in China generally last around 15 years (Chen et al., 2019). WTs started out with a rotor diameter of 17 meters in the 80s and 90s but have grown to more than 100 meters, with projections reaching up to 250 meters in diameter in future offshore wind farms (see Figure 4).

Figure 5 shows a blade being inspected up close, illustrating the size of modern wind turbine blades.
The increase of wind turbine blade (WTB) size is necessary to accommodate the increasing energy demand. However, it also suggests increased waste output in the future. According to Diez-Cañamero & Mendoza (2023) the decommissioning of these blades will have accumulated a total of 570 million ton of wind turbine waste in the EU alone by 2030. Projections for annual WTB waste are as high as 43 million tons of DWBM by 2050 (Liu & Barlow, 2017). To put this waste stream into context, the Great Pyramids of Giza are estimated to weigh a combined 13,5 million tons (Hemeda & Sonbol, 2020). This would be equivalent to more than three times the weight of the pyramids combined, a stark visualization (see Figure 6).

Figure 5: Blade inspection up close shows the huge scale of modern wind turbine blades (Gignac, 2023).

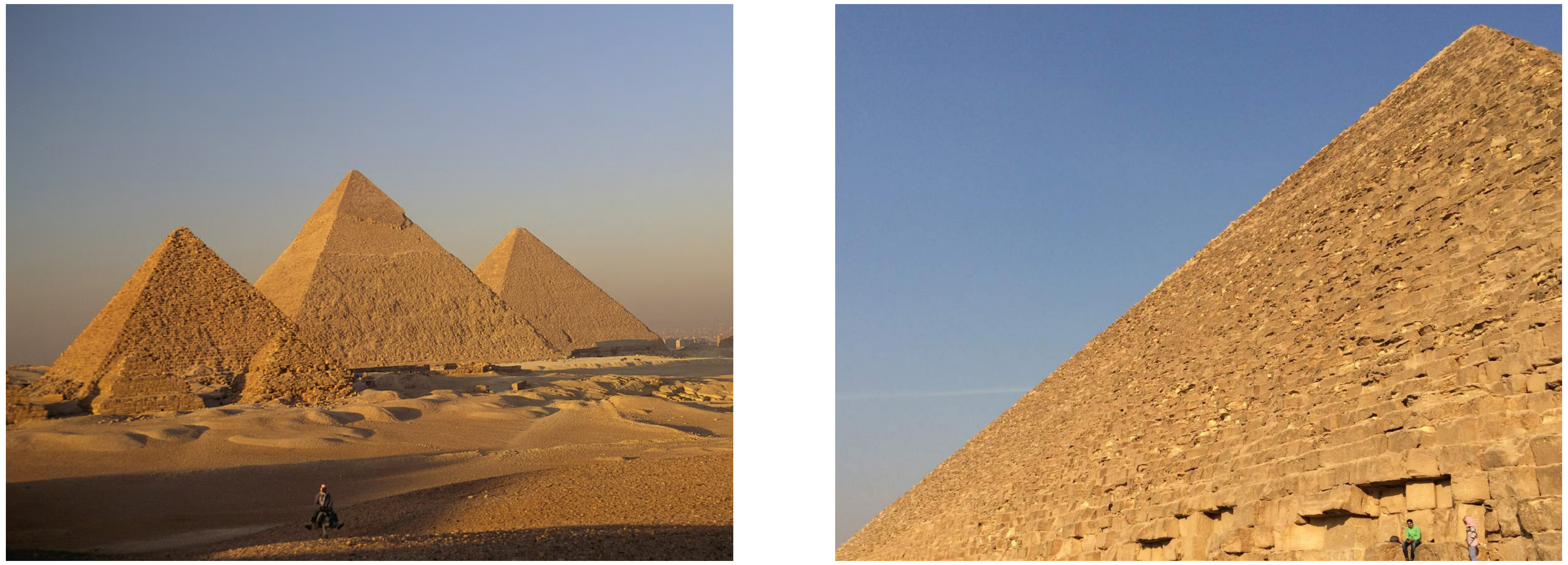


Figure 6: The Pyramids of Giza from far away and up close, with a combined weight of 13,5 million tons (McKeever & Greshko, 2023).

BLADE COMPOSITION

Now that it has been established that the WTBM waste stream is worth investigating, it is important to know what these blades are made from. To better visualize the composition of a WTB, Figures 7 and 8 show the internal structures and materials inside a typical turbine blade.

An important note is that each manufacturer designs and manufactures their own turbine blade designs, which makes each blade unique in its exact internal structure and material usage. It is, however, safe to assumes that most turbine blade designs that are active today follow similar design principles as the ones shown in Figures 7 and 8.

To achieve the optimal aerodynamic shape, WTBs are continuously varying in their cross-section, as indicated in Figure 9.

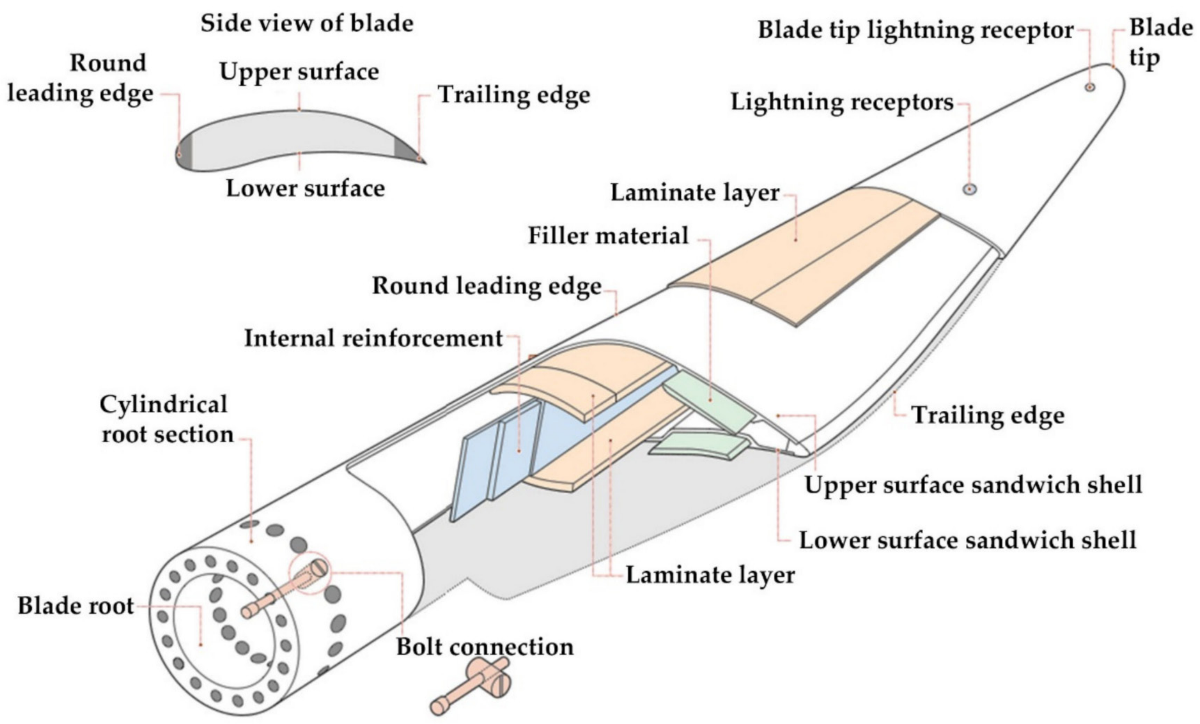


Figure 7: Internal construction of a typical wind turbine blade (Katsaprakakis et al., 2021)

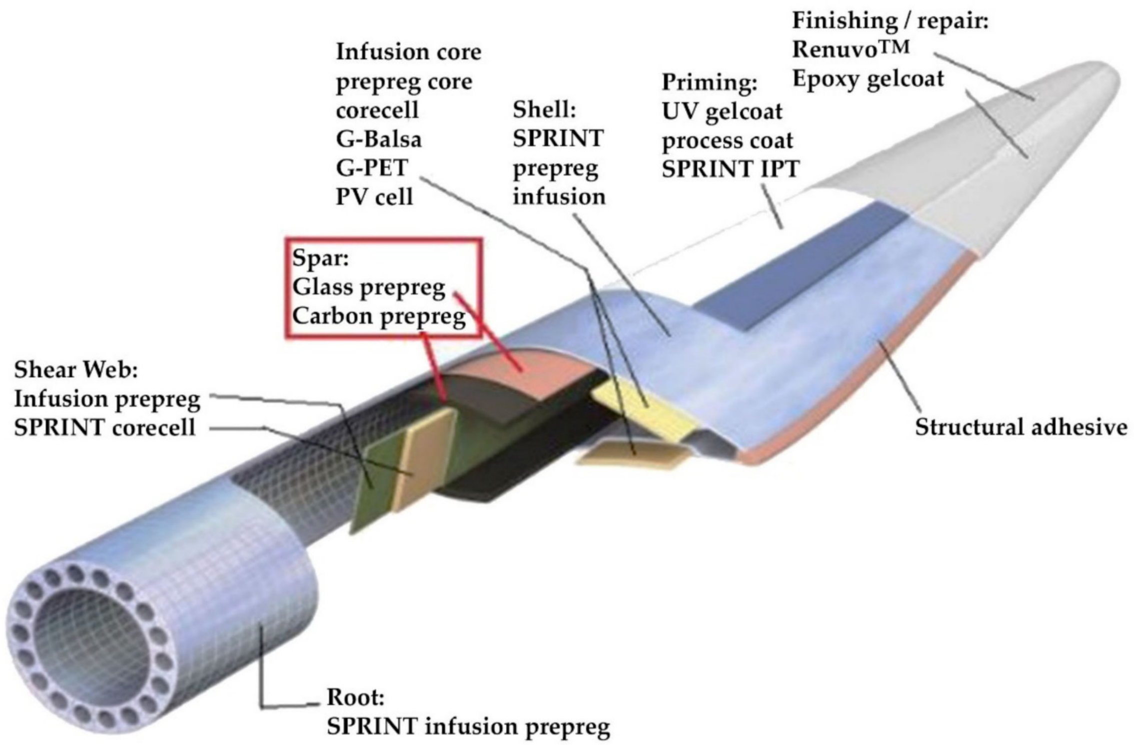


Figure 8: Typical internal material usage of a wind turbine blade (Katsaprakakis et al., 2021)

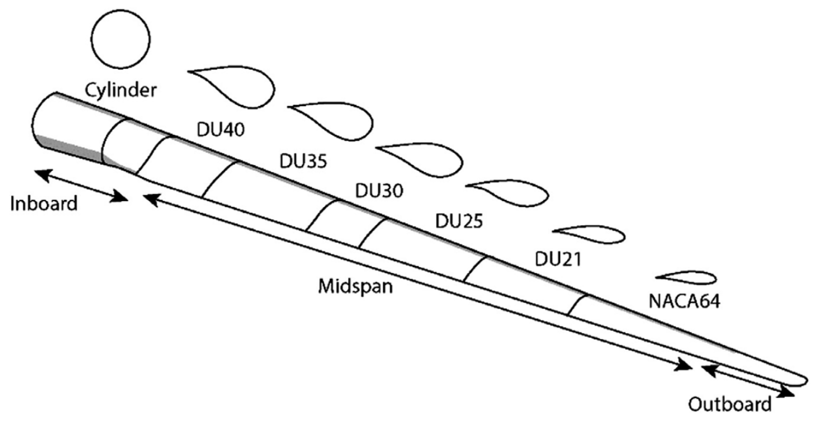


Figure 9: When cutting a blade in segments normal to its long edge, each profile has a differing geometry (Joustra et al., 2021a).

According to an overview, seen in Figure 10, made by Joustra & Flipsen (2021a), the tip of the blade that cuts into the wind is the leading edge (1), with the trailing edge (7) being all the way at the other end, where the air leaves the blade. Together, they make the main aerodynamic profile of the blade. The leading edge takes a lot of abuse as it must deal with abrasive action from particles in the wind stream that it is cutting through. The spar caps (3) and the shear webs (4) together form the main structural component of the blade, giving it most of its longitudinal stiffness. Since they experience a high bending load, they are often made from solid carbon fiber reinforced polymer (CFRP) or glass fiber reinforced polymer (GFRP). The panels (2, 5, 6) are made from a composite sandwich material and serve as the structure that transfers the forces generated by the wind to the main structure, like a wing or sail. These are often made with a GF layer with foam or balsawood core material. The panels (6) also provide additional edge-wise bending resistance experienced due to the weight of the blade on itself.

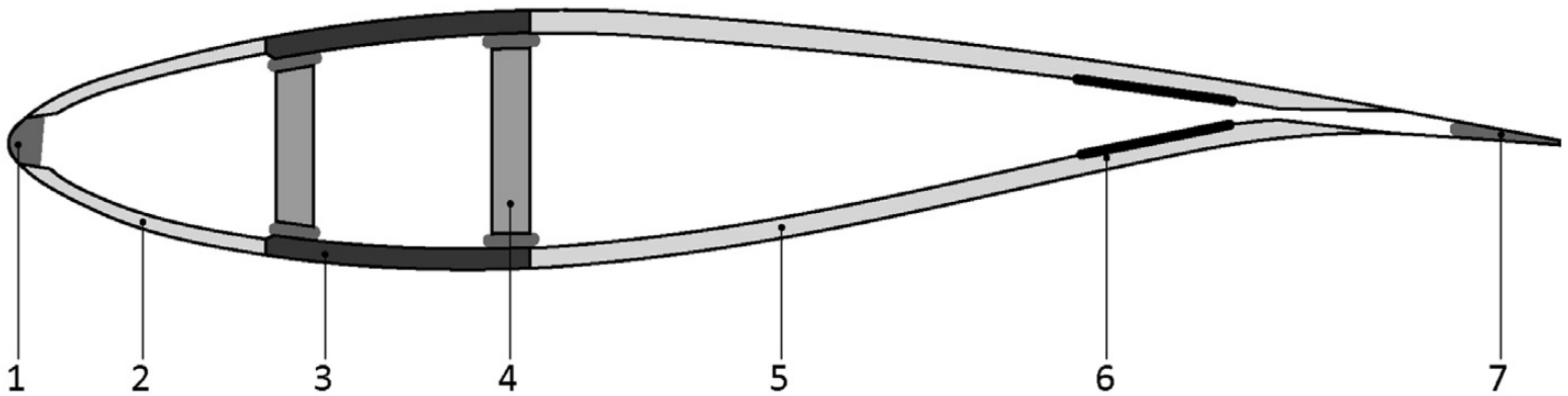


Figure 10: When viewing a blade cross section, its parts and structural design can be seen (Joustra et al., 2021b). 1: leading edge; 2: panel; 3: spar cap: 4: shear web; 5: panel; 6: panel; 7: trailing edge.

All materials used in WTBs have one thing in common: they are chosen for their high strength and stiffness under varying bending loads while remaining as light as possible. The material properties associated with this performance are flexural modulus (E_{flex}), flexural strength (σ_{flex}) and density (ρ) (Joustra et al., 2021a). Data for the specific values of these materials in active WTBs is difficult to obtain, since manufacturers keep these secret due to the highly competitive market. However, from testing materials salvaged from experimental blades and receiving data from blade prototypes one can make an overview of the material performance.

BLADE MANAGEMENT

It stands to reason that this waste stream must be managed well, otherwise the environmental benefits of the renewable energy source will be mitigated substantially. There are multiple ways of dealing with WTBs that have reached the end of their (first) service life, each with different implications. Figure 11 shows the strategies that are currently being employed to handle turbine blades that do not meet the desired efficiency anymore.

The different end-of-life strategies start at the highest amount of retained value with re-certifying or repairing an existing blade for continued operation, to the least retained value by disposing of a blade. In between these steps, several cycles can be seen including repurposing, recycling and recovery. As presented in Figure 11, each level that is removed from the original application has associated assessment criteria which include economic costs, technical feasibility, legislative support and environmental impact. The main subject of this thesis regarding the different management strategies is repurposing, highllighted by the blue diamond in Figure 11.

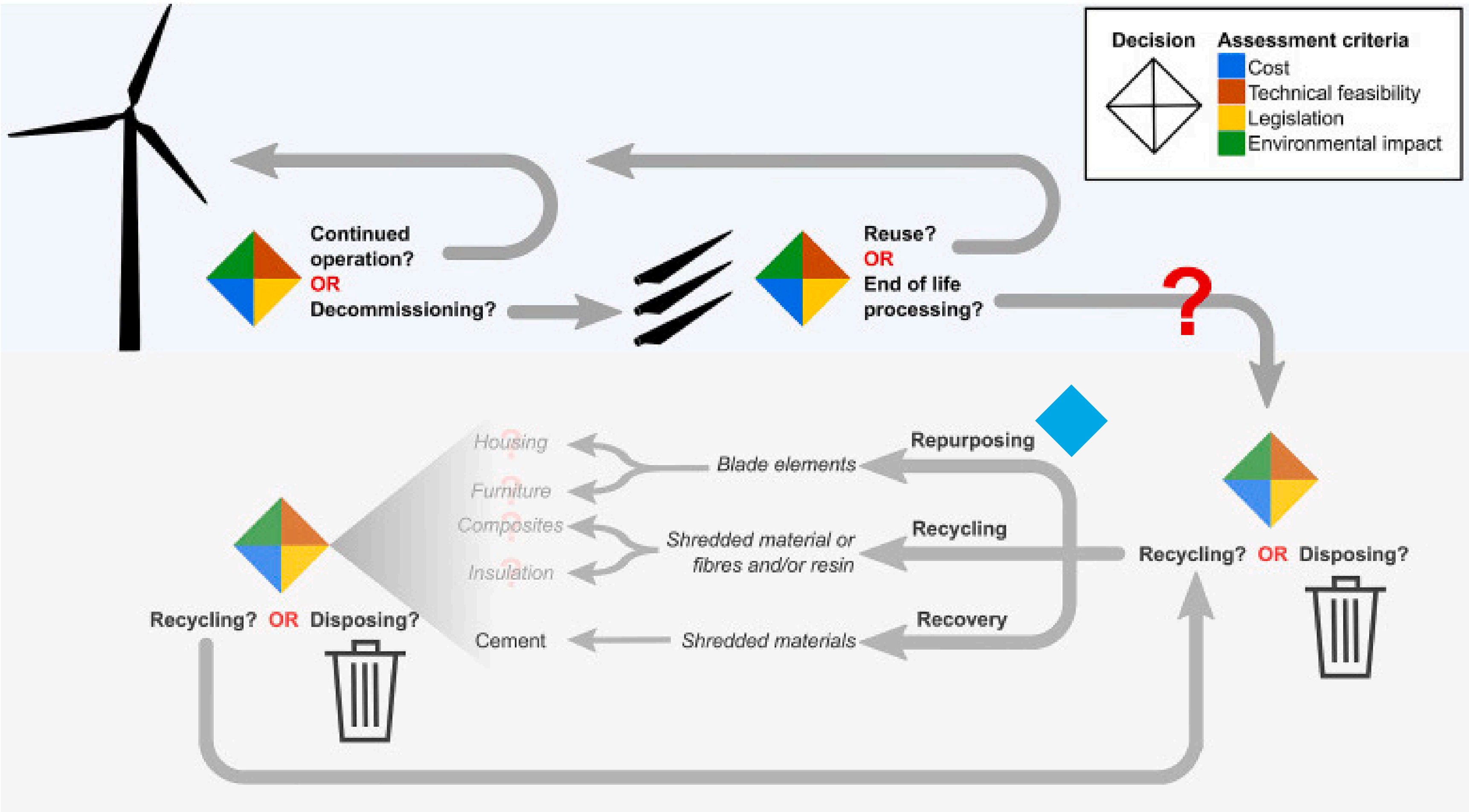


Figure 11: End-of-life strategies for wind turbine blade material (Beauson et al., 2022). More arrows mean more effort and emissions.

CONTINUED OPERATION

The least amount of associated costs and impact is achieved when a WTB in active use reaches the end of its service life but can be repaired or directly re-certified for continued use. There are guidelines that govern when this can happen, but they differ per area. For example, on the 30th of November 2020 the Danish government issued Executive Order no. 1773, containing a revision on technical certification and servicing of wind turbines (Danish Energy Agency, 2020). Next to this, there is a life extension certificate from Det Norske Veritas and Germanischer Lloyd (DNV GL) aptly called DNV-ST-0262 Lifetime extension of wind turbines standard which can extend the duration of both off- and onshore wind turbines (DNV-ST-0262 Lifetime Extension of Wind Turbines, 2021).

Blades can sometimes be re-certified without much additional effort; however, wear, damage and decreased efficiency often require repair and/or upgrades. Upgrading an existing blade that has fallen behind on efficiency can be done by adding vortex generators, as seen in Figure 12, to an existing wind turbine (Siemens Gamesa Renewable Energy (SGRE), n.d.).

Figure 12: Strips of vortex generators installed on existing wind turbines can provide 2-5% more power generation annually (Siemens Gamesa Renewable Energy (SGRE), n.d.).

A common cause for loss of blade efficiency is damage, such as presented in Figures 13 - 17 (Danish Energy Agency, 2020) (Katsaprakakis et al., 2021). Various repair methods can be employed but they are out of scope of this thesis and, as such, are not reviewed here.

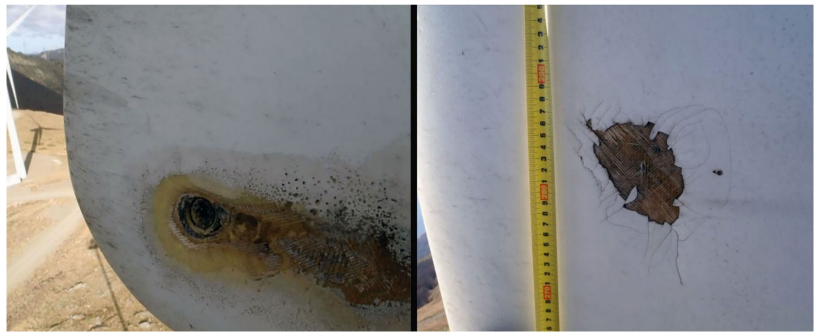


Figure 13: Lightning strike damage on the tip of a blade, with local charring and delamination visible (Katsaprakakis et al., 2021).

Figure 14: Shell delamination and detachment due to lightning strikes on blade tips (Katsaprakakis et al., 2021).

Figure 15: Shell debonding on join line between shell halves (Katsaprakakis et al., 2021).

Figure 16: Examples of leading edge erosion due to wind-blown particles (Katsaprakakis et al., 2021).

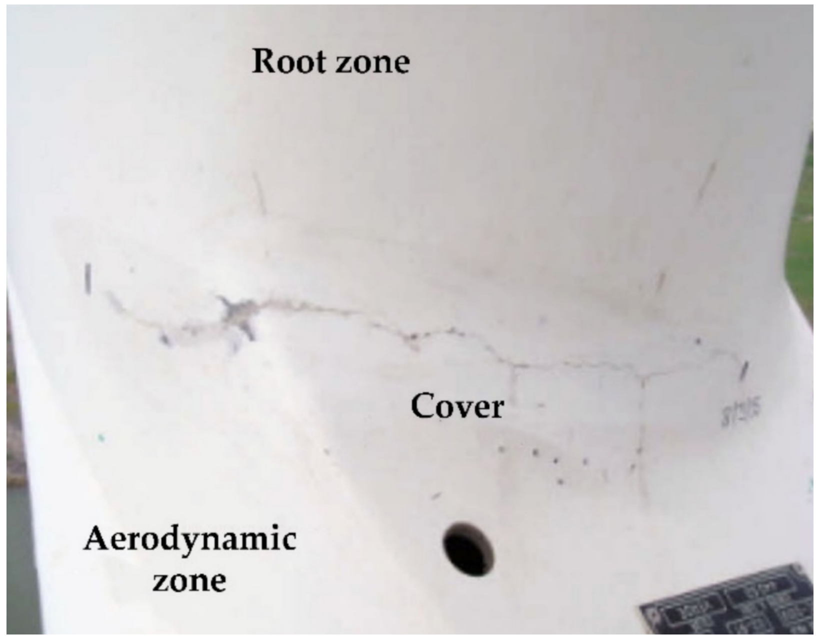


Figure 17: Fatigue damage at the root of a blade where it attaches to the hub (Katsaprakakis et al., 2021).

While maintaining, repairing and upgrading a WTB does postpone the decommissioning of the blade, the efficiency and blade integrity will, eventually, fall below a safety- or economic threshold which warrants the decommissioning of the blade. After decommissioning, other strategies come into play.

REUSE/REPOWER

After its first service life, the blade might be less efficient but still viable for less demanding or stringent operations. When this is the case, a turbine blade or even a whole wind turbine can be disassembled and transported to a new location to keep functioning as an energy source. Some businesses have emerged that handle in secondhand wind turbines and wind turbine components (Repowering, n.d.) (Repowering Turbines Arkiv, n.d.). Evaluating wind turbine degradation due to fatigue and other damage mechanisms is necessary, but challenging.

RECYCLE/RECOVER

When blade damage is too great for repair or its service life can no longer be recertified, the blade is decommissioned. However, the separate materials that make up the blade still possess value, which can be extracted. Multiple techniques to extract singular materials from the composites inside the blade have been developed. Recycling WTBM is challenging, since it is mostly constructed from composite materials which are notoriously difficult to recycle (Beauson et al., 2022). There are four main processes for recycling/ recovering composite materials: mechanical, pyrolysis, oxidation in fluidized bed and chemical. An overview of each method can be seen in Table 1 and 2. The various

Table 1: Overview of different WTBM recycle strategies (Jani et al., 2022).

Recycling process	Description
Mechanical	The composites are decomposed through grinding, crushing, shredding, milling or any other kind of cutting methods. The subsequent material can be isolated into resins and fibers goods
Pyrolysis	In the absence of oxygen, the composite is heated to 450°C to 700°C; the polymeric resin is transformed to a gas or vapor, while the fibers remain inert and are subsequently retrieved
Oxidation in fluidized bed	At temperatures ranging from 450°C to 550°C, the polymeric matrix is combusted in a hot, oxygen-rich air flow.
Chemical	The fibers are recovered when the polymeric resin is broken down into oils

Table 2: Overview of applications for recovered material per recycling strategy (Jani et al., 2022).

Method	Process	Applications of recovered products
Mechanical	Grinding, shredding, crushing and milling	• Glass fiber (GF) and carbon fiber (CF) and Aramid fibers can be reused to make new composites • Used in bulk molding compounds (BMCs) as an alternative to the virgin fibers (VF) (10% wt.) • Shredded composites are utilized to replace VFs in new composites • In concrete with a cement-based matrix, short GFs can be employed • In Portland cement concrete, recovered GFs are utilized as reinforcing element
Thermal	Pyrolysis	• Fabricate glass-ceramic products • Create novel composites of low-density polyethylene (LDPE) matrix with 15% reinforcement of recycled fibers (RF).
Thermal	Fluidized bed process	• Recovered GFs are consumed for BMC products manufacturing • Dough molding compounds (DMCs) headlamp molding • Production of thermo-electric composites
Hybrid	Microwave pyrolysis	• RFs are utilized to fabricate novel thermoset composite material • Extrusion and injection molding are utilized to make composites out of recovered CFs with a polypropylene and nylon matrix.

thermal/chemical recycling strategies aim to extract one or more base materials from the composite to reuse in the manufacturing of new composite materials such as concrete. While these techniques are interesting, this thesis will not elaborate on them due to scope limitations.

Mechanical recycling refers to simply shredding the material to use as a bulk filler for building material. This is not always economically viable due to the awkward shape and size of WTBs, cutting them up using big vehicle mounted saws (see Figure 18), transporting the segments to a facility and shredding them may end up costing more than what is gained.

Some companies do make products that incorporate this shredded composite material, such as MILJØSKÆRM® which makes sound barriers filled with fiberglass composite granulate, as shown in Figure 19 (Miljøskærm, 2021).

Figure 18: Excavator mounted diamond tipped saw cuts into a WTB (Echidna Excavator Attachments, n.d.).

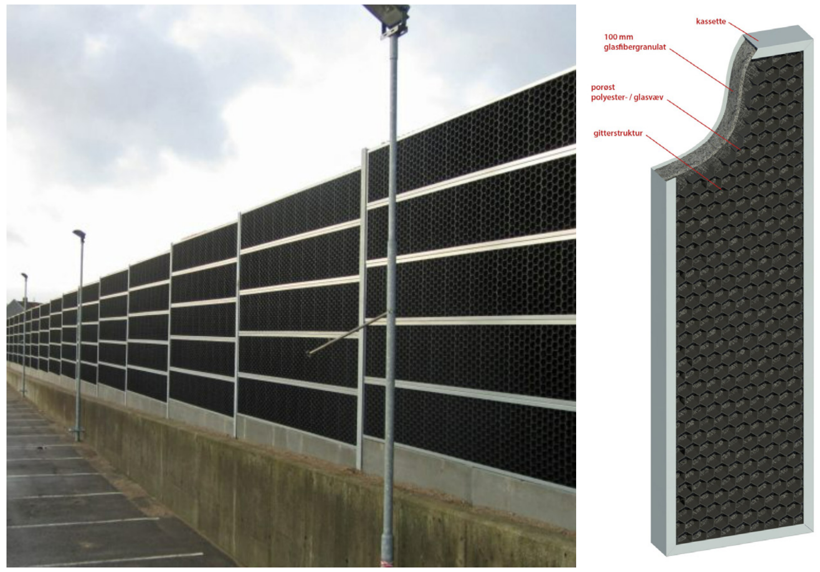


Figure 19: Noise barrier filled with mechanically recycled glass fibre composite granulate (Miljøskærm, 2021).

DISPOSAL

When nothing else is viable, WTBM is also disposed of in landfills (Figure 20). This is often one of the cheapest options but also throws away all the potential remaining value inside the material. Luckily, there is no leaching of contaminates into the ground water due to landfilled WTBM (American Clean Power Association, 2022).

However, recently at the Spanish Wind Energy Association (AAE)'s annual congress, WindEurope called for a complete ban on landfilling DWBM by 2025, stating that this would further accelerate the development of more sustainable alternative end-of-life recycling technologies (Wind Industry Calls for Europe-wide Ban on Landfilling Turbine Blades, 2021).

Figure 20: Scrapped wind turbine blades being buried under a layer of earth (Adobe Stock).

REPURPOSE

Out of all the end-of-life options, repurposing possesses the most opportunity to find innovative and sustainable usage of WTB materials. In this case, not the individual single materials inside the composites are being reused, but entire sections. By leaving the original material partly intact, their high-performance characteristics are preserved. Next to this, an eco-audit done by Morini et al. (2021) shows that repurposing WTBM can significantly reduce the environmental impact of a WTB when compared to landfill. Most currently known repurpose strategies focus on the structural capabilities of the materials, their high flexural modulus and comparatively low density. Examples of these structural repurposing strategies can be seen in figures 21 - 26.

Figure 21: A rather striking example of repurposing WTBM by constructing a picknick table from sandwich material (Joustra et al., 2021b).

All these examples employ what is dubbed by some as 'structural reuse' where the focus is to exploit the excellent load bearing capabilities of the structures and materials of a WTB. However, not all repurpose examples are purely structural in design, as shown by the sound barrier wall seen in Figure 26. Here, the acoustic absorption, transmission and reflection of the WTBM is exploited to keep sound from entering a specific area. Few other repurposing applications which make use of material properties other than flexural modulus and flexural strength versus density were found. There is evidence of a knowledge gap, which will be explored in the application finding chapter.

Figure 22: A lookout tower with a WTB as the main support structure (left) and a playground made from WTB sections (right) designed by Superuse spin-off Blade-made (Blade-made, n.d.).

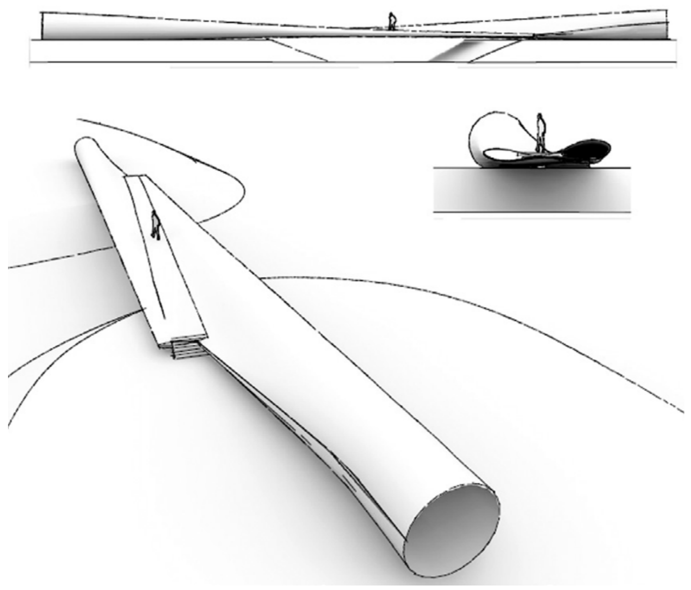


Figure 23: A pedestrian bridge concept made from two complete WTBs designed by Superuse studio (Jensen & Skelton, 2018).

Figure 24: The first pedestrian bridge made from WTBs designed and installed by Poland-based Anmet (Mason, 2021)

Figure 25: Emergency housing concept using WTB sections as a roof and blade root sections as structural support (Bank et al., 2018).

Figure 26: A sound barrier made from interlocking WTB sections (Blade-made, n.d.).

APPLICATION FINDING

This brings us to the purpose of this project: are there any other suitable applications for the repurposing of WTBM next to structural? Since little is known about acoustic properties of WTBM, the scope of this thesis is narrowed down to identifying possible applications of WTBM based on their acoustic properties. Finding novel applications in this area requires the use of specific methods to accurately examine different materials within a reasonable timeframe. One such methods, which is used in this project, is CATSS.

CATSS: APPLICATION FINDING METHOD

To take a material property driven approach to the application finding, the Circular applications through selection strategies (CATSS) method was used (Carrete et al., 2023). This method is derived from the Material driven design (MDD) method, where material data is the starting point of a design project and applications that benefit from the selected material properties. This way, specific materials can be matched to real world applications, which is particularly valuable when dealing with end-of-life materials. There are three strategies within CATSS to match material data to applications:

1. Substitution
2. Selection by function
3. Inverse selection

In this thesis, substitution and selection by function are the main drivers for finding suitable applications.

SUBSTITUTION

This path of CATSS looks at existing applications that can be found on the market or in literature that could be contenders for using the material. Here, the selection consists of iterative rounds of feasibility studies, with each round becoming more in-depth and material property-dependent. The final applications that emerge are cross referenced with known material properties and measured against existing norms and standards that exist for the application.

Application finding using Ansys Granta Edupack search function.

The Ansys Granta Edupack material property database software package can be used as a tool for investigating and comparing relevant material data. However, it also contains a search engine which is able to look for keywords in the complete description of every material in the database. By providing appropriate keywords, data regarding potential acoustic applications may be found.

The relevant keywords in this project are:

- Acoustic
- Sound
- Vibration
- Noise

The search results are categorized into materials, processes and other categories such as producers which can be selected to highlight where in the document the keyword shows up (see Figure 27).

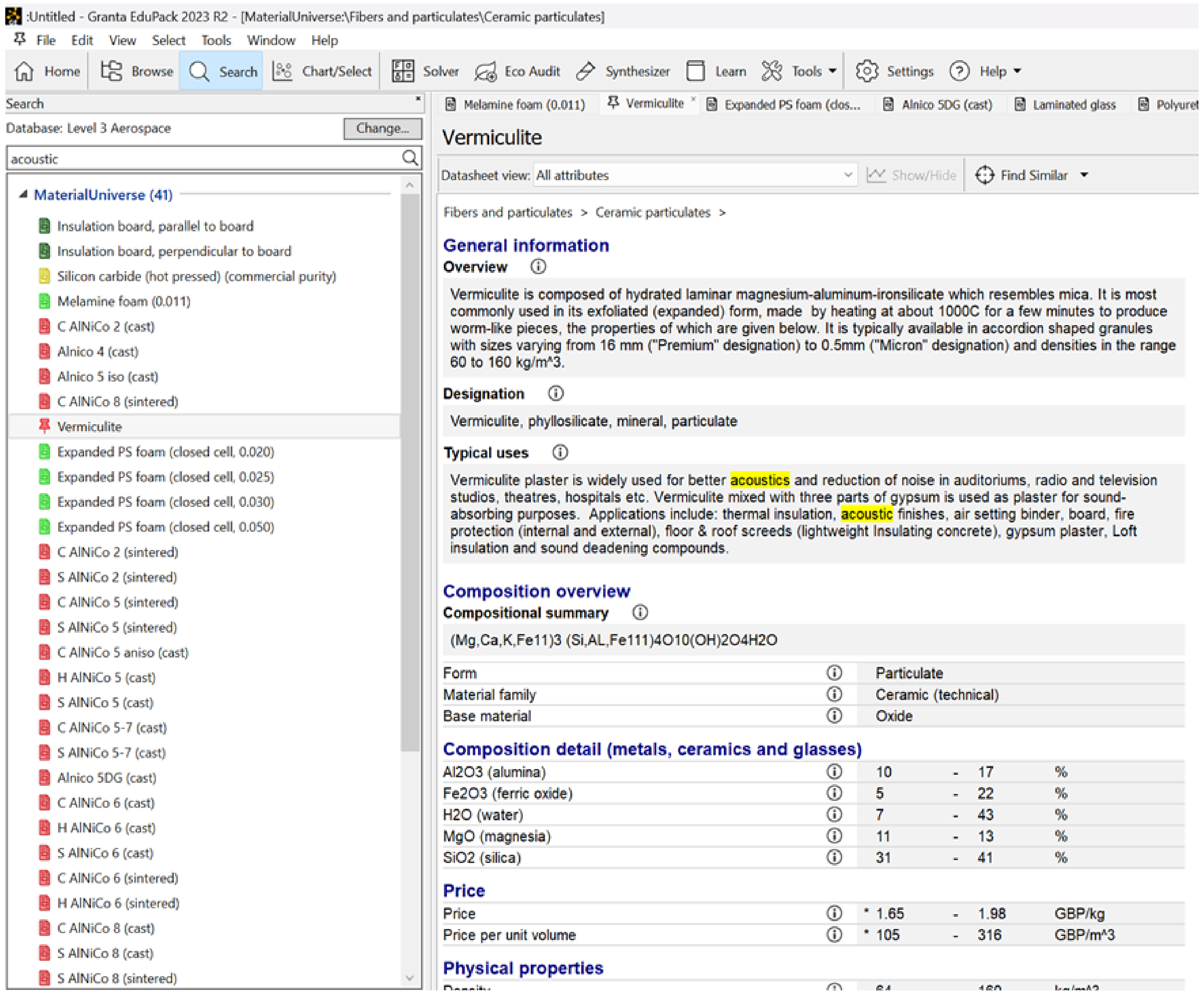


Figure 27: Example of a keyword search in the Ansys Granta Edupack database (Ansys GRANTA Edupack software, 2024).

The complete set of materials that resulted from the search function using the four keywords (acoustic, sound, vibration, and noise) yielded no applications of particular interest. Most applications identified by the search function mentioned acoustic or vibrational dampening, where some other applications mentioned material usage inside complex acoustic products such as amplifiers or electro-acoustic pickups. These applications, however, are not relevant in the context of DWBM since they rely on very small electronic parts (which are impossible to make from WTBM) or material properties that are not present in WTBM, such as the ability to conduct electricity.

SELECTION BY FUNCTION

Another path of CATSS starts by looking at the material itself, where its macro- and microscopic properties are evaluated and plotted in a performance index. This performance index is then referenced to known material groups and overlapping areas are identified. These overlapping areas define what the material excels at, which can, in turn, be linked to applications in which this specific material property is important (substitution path).

An important start to this method is looking at the relevant available data in the Ansys Granta Edupack database, since this is the basis of a material performance mapping. In the case of acoustics, a few material properties can be identified as relevant to the acoustic properties of materials. However, there is not one single definition of acoustic properties for any given material. The following acoustic material property categories can be identified:

- Absorption: dissipating airborne acoustic waves
- Dampening: reducing acoustic vibration within a structure
- Reflection: Returning acoustic waves opposite to the angle of incidence on a surface
- Refraction: Changing the angle of direction of the path of acoustic waves
- Transmission: Letting an acoustic wave travel through a medium
- Resonance: Self-amplification of an oscillating system by incoming soundwaves
- Emission: Production of soundwaves by an oscillating system

Each category listed above has its own set of (material) properties that influence them (see Table 3).

Figure 28 shows how soundwaves interact with a material when reflecting, transmitting or absorbing.

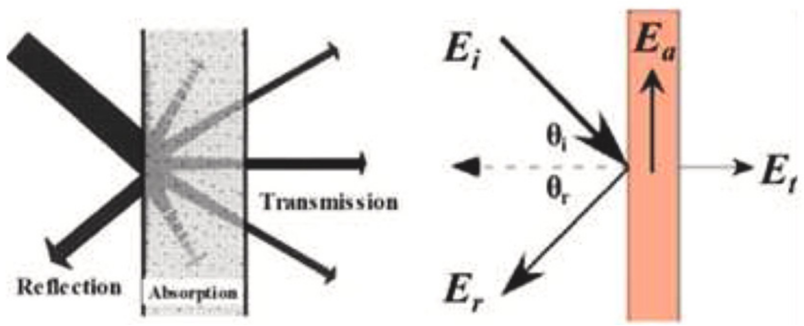


Figure 28: Various ways sound interacts with materials when it strikes the surface (Sujon et al., 2021).

Table 3: An overview of material properties that influence various categories of acoustic properties.

Absorption	α (sound absorption coefficient) ρ (density) Surface finish/roughness (Payette, 2018) Material thickness
Dampening	Tanδ (mechanical loss coefficient) ρ Material thickness
Reflection	Surface finish/roughness E (Young's modulus) ρ
Refraction	ρ
Transmission	Transmission Loss $(E/\rho)^{1/2}$ (acoustic velocity/specific stiffness)
Emission/Resonance	E ρ $z=E\rho^{1/2}$ (characteristic impedance) tanδ $R=(E/\rho^3)^{1/2}$ [radiation ratio] $ACE=([E/\rho^3]^{1/2})/\tan\delta$ (acoustic converting efficiency)

As shown in table 3, many acoustic properties are derived from either the density ρ or the Young's Modulus E or a combination of both. It is, therefore, reasonable to say that these properties combined can give an indication of the potential acoustic performance of a given material. These material properties are commonly used in a variety of other fields, so accurate data for many material types is available in Ansys Granta Edupack.

MATERIAL PROPERTY MAPPING THROUGH ANSYS GRANTA EDUPACK

To identify materials with similar acoustic properties to WTBM, the right material properties need to be mapped for comparison. From the literature that was found, Young's modulus and density are both key factors in acoustic behaviour and are therefore suitable material properties for mapping. To begin, known material data from a WTBM test panel was loaded into Ansys Granta Edupack, provided by J.Joustra. Next to this, a custom composite sandwich material was constructed using the multi-layer material synthesizer tool (as seen in figure 29).

The sandwich material was based on the WTBM test panels used for the impedance tube testing. A bubble chart with Flexural modulus on the Y-axis of the chart was chosen (see Figure 30). This was done because it is similar to the Young's modulus but indicates stiffness under a bending load which is applicable for acoustics since sound waves exert a bending moment on panels at small scale (Angus, 2002). The X-axis shows the density of the material in kg/m^3. The database used to generate the chart was level 3 ecodesign, with all materials visible.[1]

Naturally, this bubble chart merely provides a very general overview of where materials lie compared to each other. Nothing definitive can be said about the characteristics of WTBM relative to other materials without an appropriate performance index. A performance index will show which materials share a similar ratio of material properties.

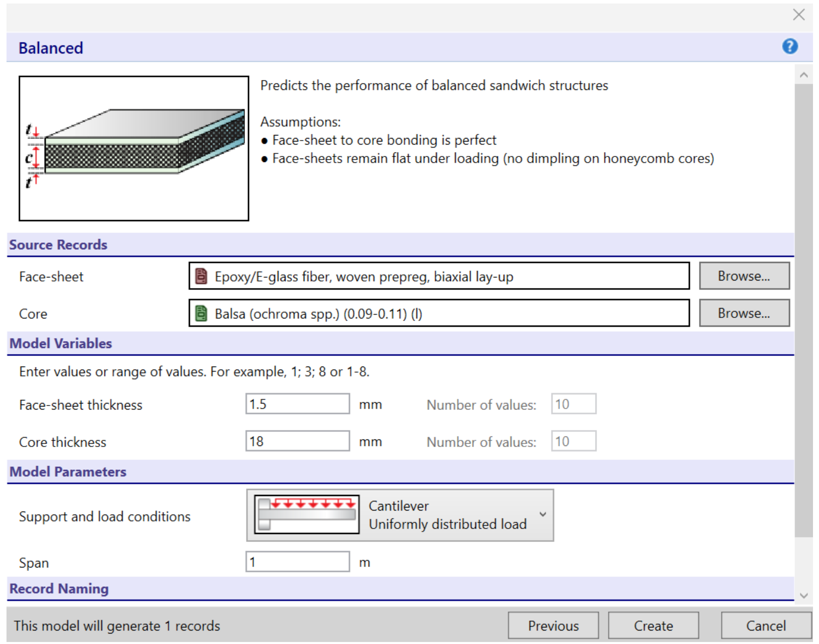


Figure 29: Ansys Granta Edupack synthesizer tool for making custom multi-layered materials, showing the WTBM consisting of 1.5 mm GF sheets with a Balsa wood (longitudinal) core (Ansys Granta Edupack, n.d.).

1 Ansys Granta Edupack is a material property database with multiple levels of complexity, ranging from level 1 to level 3. When looking for the average property range of a general material group quickly, one would select level 1. Various specializations added on top of the higher levels exist, such as aerospace and ecodesign. Level 3 ecodesign has many specific materials with narrow property ranges and added information regarding environmental impact.

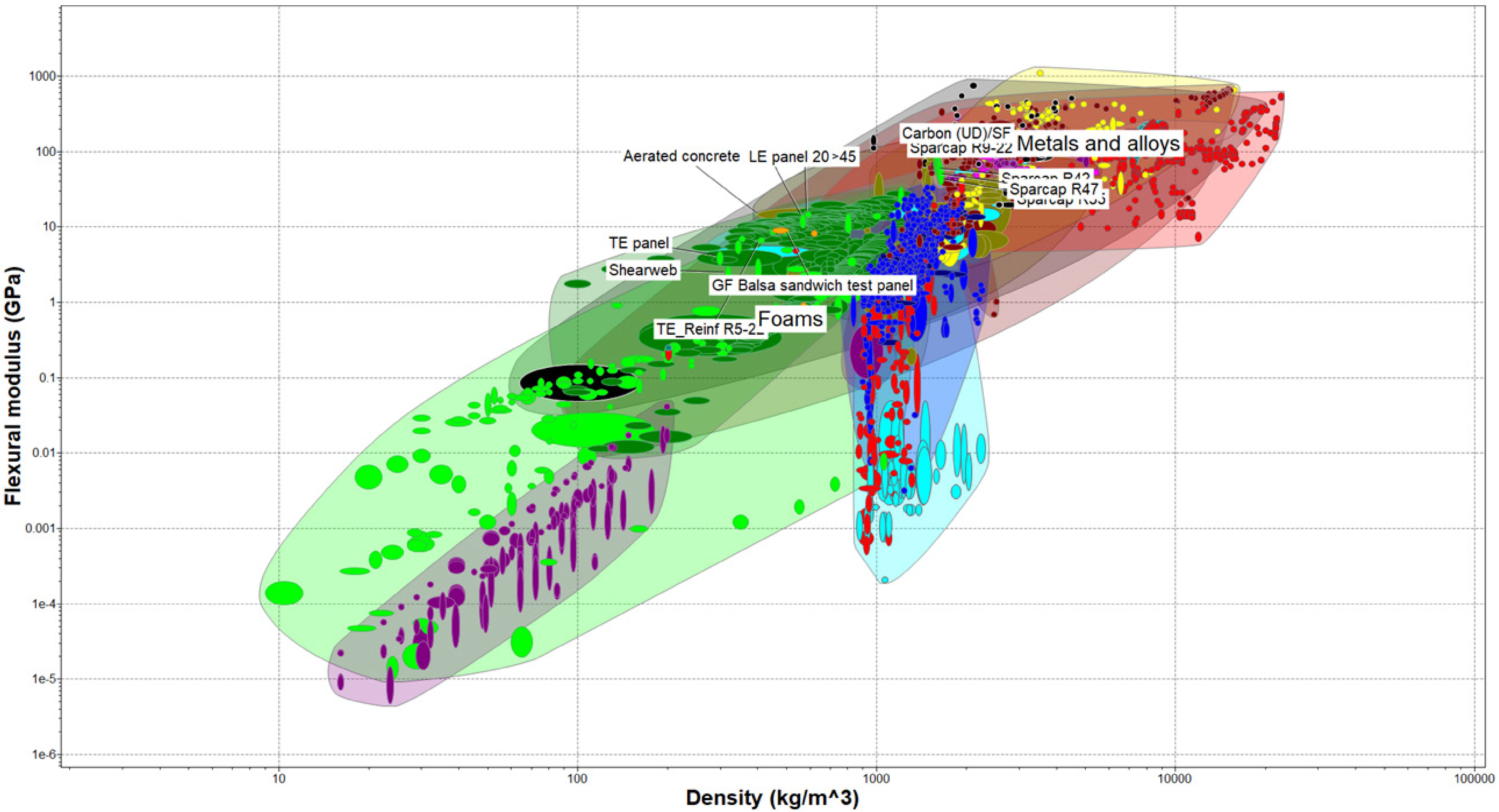


Figure 30: Bubble chart of all level 3 ecodesign materials in Ansys Granta Edupack, with flexural modulus on the Y-axis and density on the X-axis (Ansys GRANTA Edupack software, 2024).

Performance index 1: Direct substitution

This method involves looking at materials with an exact match in flexural modulus and density, which can be done by drawing a limiter box around the reference material. The reference material is the custom-made sandwich material representing the GF-balsa-GF WTBM panel (shown in orange in Fig. 31). As seen in Figure 31, when the limiter box is drawn around the reference material and the view is scaled, materials with near-identical material properties are identified.

The materials that directly or partially overlap the reference material are all various types of wood or other WTBM sandwich panels that were loaded into the software. The types of wood shown are some of the more high-performance varieties, such as Picea Sitchensis (also known as Sitka Spruce) which is widely used as building material for high bending stiffness lightweight construction. For example, Sitka Spruce is often used in gliders and was extensively used during the second World War for manufacturing Mosquito bombers (National Plant Data Center et al., 2002). Next to this, Sitka Spruce, Okoume, Maple and other woods selected by the limiting box are used in acoustic instruments.

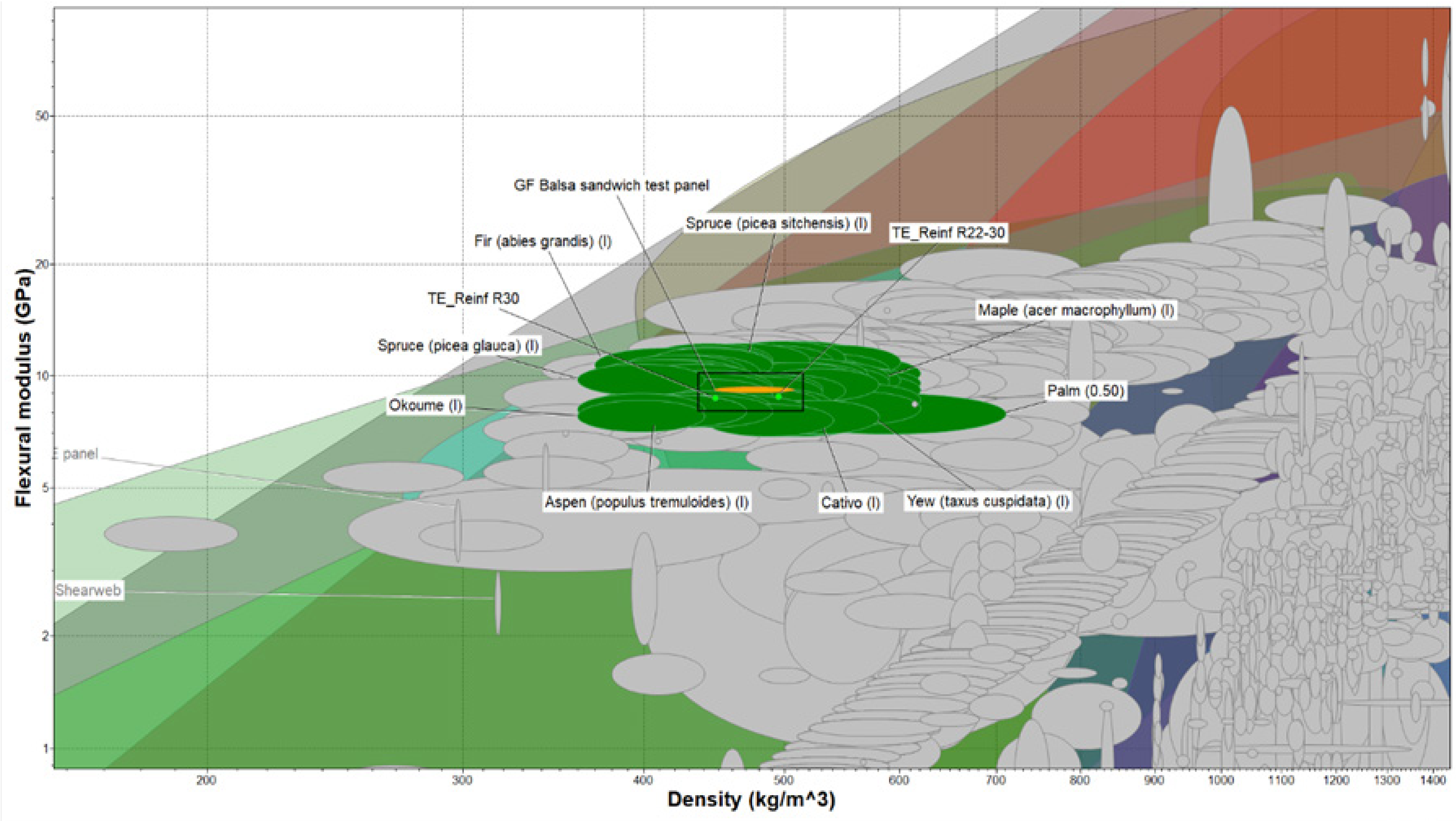


Figure 31: Scaled view of a limiter box drawn around the reference material shown in orange, all materials that have an overlap with this boxed area remain visible (Ansys GANTA Edupack software, 2024).

Performance index 2: Acoustic velocity

Since direct substitution excludes many materials that have a potentially better performance, another performance index needs to be constructed. In Table 3, a list of material properties related to acoustic performances shows one of particular interest: the acoustic velocity ($\mathbf{AV}$). This metric is defined as follows:

$$AV = (E/\rho)^{1/2}$$

Another name for the metric $\mathbf{AV}$ is Specific Stiffness. Here, the acoustic value indicates how quickly a soundwave travels through a material in m/s (Ansys Granta Edupack, n.d.). For material selection, Ansys Granta mentions the following notes on acoustic velocity: "Values for the $\mathbf{AV}$ can be used to select materials that transmit sound easily, versus those that absorb sound. This information be used in product design to optimize the effect of transmitted sound waves. Materials with a high $\mathbf{AV}$ will also exhibit higher pitch and resonant frequency. Therefore, for a fixed shape the choice of material can alter whether a component resonates when subjected to vibrations." (Ansys GRANTA Edupack software, 2024). Here, sound transmission, sound emission pitch and resonance can be predicted by looking at the $\mathbf{AV}$ of the material. This provides an excellent acoustic performance index for identifying more materials in the bubble chart. To be able to compare the $\mathbf{AV}$ of materials in the chart, the performance index can be plotted as a line. By taking logs of the formula of $\mathbf{AV}$, the following condition

$$\mathrm{Log}(E) = 2\mathrm{Log}(\rho) + 2\mathrm{Log}(AV)$$

gives a family of straight parallel lines of slope 2 on a plot of $\mathrm{Log}(E)$ against $\mathrm{Log}(\rho)$, where each line corresponds to a value of the constant $\mathbf{AV}$. Thus, by plotting the performance index in the bubble chart as a line with slope 2, starting from the $\mathbf{AV}$ of the reference WTBM, materials along this line share the same $\mathbf{AV}$ (see Figure 32).

Here, the materials closely surrounding the performance index slope remain and the materials above and below it are greyed-out. This is done since a higher or lower $\mathbf{AV}$ is not directly indicative of better or worse acoustic performance, and therefore the desired materials need identical or similar acoustic behavior to WTBM to be substituted. Various wood varieties remain, as well as glass foam, polyvinyl chloride (PVC) foam, kenaf fiber and ramie fiber. Other exotic materials are also left but are not considered due to their high cost or low availability.

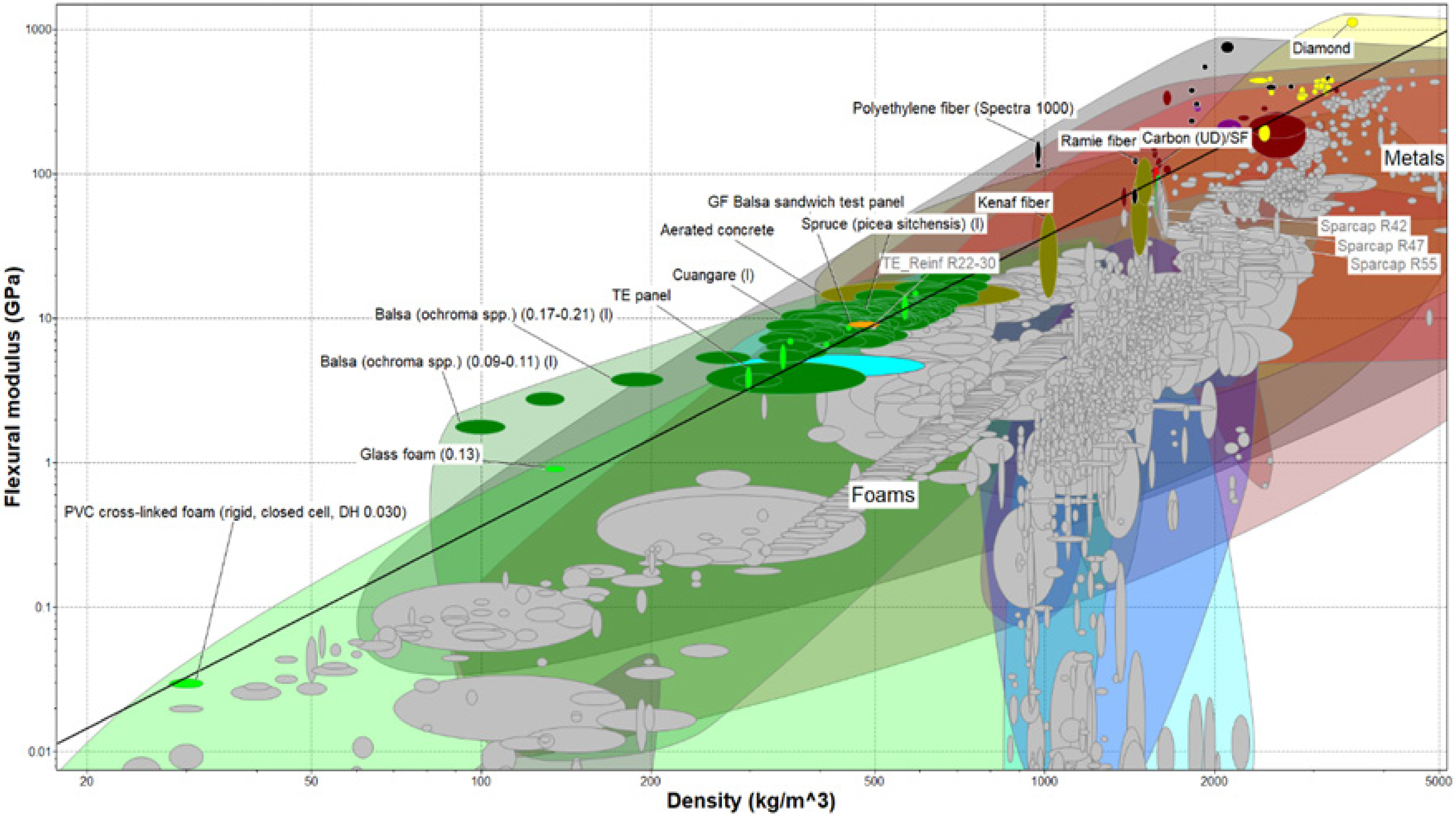


Figure 32: Performance chart in Ansys Granta Edupack with an AV performance index with a slope of two, centred on the GF Balsa sandwich test panel highlighted in orange (Ansys GRANTA Edupack software, 2024).

Performance index 3: Panel bending

According to Angus (2002), there are two main transduction mechanisms through which sound waves propagating through a thin plate emit sound: transverse shear waves and bending flexural waves. In a transverse shear wave (see Figure 33), all the acoustic energy is translated into pure shear force: sections inside the material that move parallel to each other, resisting the deformation in the form of the shear modulus (G) of the material.

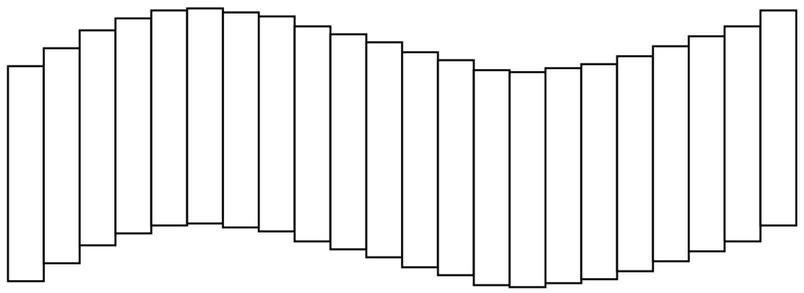


Figure 33: A transverse shear wave in a thin plate represented by microscopic sections moving past each other (Angus, 2002).

The shear modulus of a material is related to its Young's modulus (E) with the Poisson's ratio (v) using the formula:

$$G = (E / (2(v + 1)))$$

The acoustic velocity for pure shear wave propagation is then given by the formula:

$$AV_{shear} = (G/\rho)^{1/2}$$

Note that this last formula resembles that of the AV given earlier, with the E replaced by G. However, according to Angus (2002), shear forces contribute only small amounts to the displacement of a material due to acoustic waves. Most of the acoustic energy inside a thin panel propagates in the form of bending waves (see Figure 34).

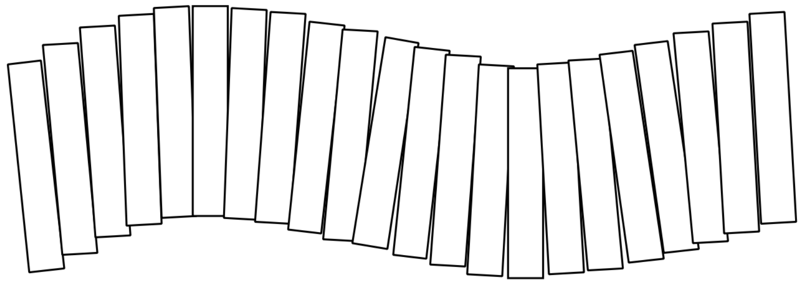


Figure 34: A bending flexural wave added to the transverse shear wave in a thin plate, represented by microscopic sections moving past each other and bending away from the neutral line (Angus, 2002).

According to Ansys GRANTA Edupack software (2024), the performance index of a panel in bending can be characterized using the following formula:

$$S = (E/\rho)^{1/3}$$

Once more, the Young's modulus and density of the material are key in describing acoustic performance. The performance index can then be plotted as a line by taking logs of the formula of S

$$\mathrm{Log}(E) = 3\mathrm{Log}(\rho) + 3\mathrm{Log}(S)$$

which gives a family of straight parallel lines of slope 3 on a plot of $\mathrm{Log}(E)$ against $\mathrm{Log}(\rho)$, where each line corresponds to a value of the constant S.

When placing the third performance index into the bubble chart, starting at the S of the reference WTBM, the following chart is produced (see Figure 35 on page 34).

Here, various foam materials in the bottom left have a similar ratio between the plotted material properties compared to the reference material, including PVC foam and expanded polystyrene foam. Vermiculite and insulation board also share similar ratios between flexural modulus and density compared to the reference material. Vermiculite is a curious material to show up in this comparison, it is a technical ceramic particulate mainly used as an additive in plaster for sound deadening applications. However, since the material properties of WTBM do not survive when ground to a particulate, this material is not relevant in the search for applications.

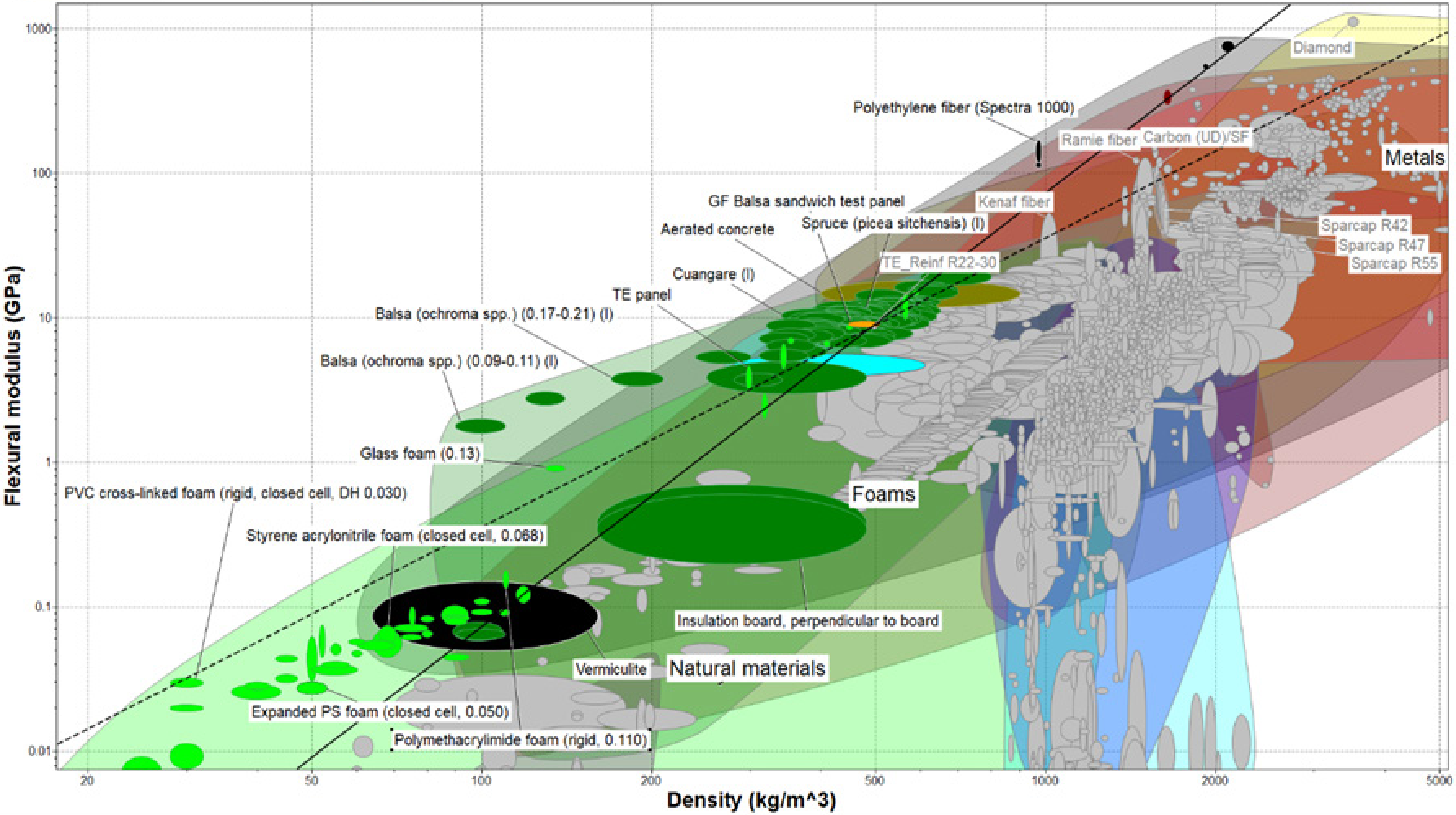


Figure 35: Performance chart in Ansys Granta Edupack with a panel bending performance index with a slope of three, centred on the GF Balsa sandwich test panel (orange) (Ansys Granta Edupack, n.d.).

MATERIAL PERFORMANCE LINK TO APPLICATIONS

After identifying materials with similar relevant material properties, acoustic applications that these materials are used in were identified. Through online searches combining the material with keywords such as 'acoustic', 'sound' and 'applications' various applications were identified. Table 4 presents an overview of these identified applications for each material.

Table 4: Identified materials that are relevant to this project and acoustic applications linked to these materials.

Sitka spruce	Toneboards for acoustic instruments, DML
Balsa wood	Sound insulator, DML*
Vermiculite	Sound insulator, sound deadening
Expanded polystyrene foam (closed cell, 0.050)	Sound insulator, DML
PVC cross-linked foam (rigid, closed cell, DH 0.030)	Sound insulator
Glass foam	Sound insulator
Aerated concrete	Sound absorption**
Insulation board/Fiberboard	Sound deadening, DML

*DML: Distributed mode loudspeaker.
**Aerated concrete on its own has poor sound absorption qualities, but when paired with Helmholz resonator cavities the absorption coefficient can be raised to 0.6 (Laukaitis & Fiks, 2006).

ACOUSTIC KNOWLEDGE GAP

Many of the identified materials are used for the absorption of sound or to prevent sound from entering a certain environment. However, the results in table 4 are all based on mechanical material properties, not direct acoustic measurements. Literature on acoustic performance of (composite) materials is scarce and Ansys Granta Edupack contains very little information regarding acoustic material properties. Therefore, it can be concluded that there is a knowledge gap when regarding the acoustic properties of WTBM. To fill in this gap, measurements need to be conducted to find relevant acoustic properties of WTBM. This knowledge gap is part of the reason for the focus on acoustic applications of this thesis, since there is an opportunity to generate new and impactful insights.

SPECIFIC ACOUSTIC APPLICATION - DML

A number of the materials found during the selection phase are currently used in a particular acoustic application when it is in panel form: a Distributed Model Loudspeaker (DML). This application uses an exciter to vibrate a thin panel to reproduce a highly dispersed sound field (see Figure 36). According to Luo (2011) the panel material has a significant influence on the sound output of a DML, with frequencies

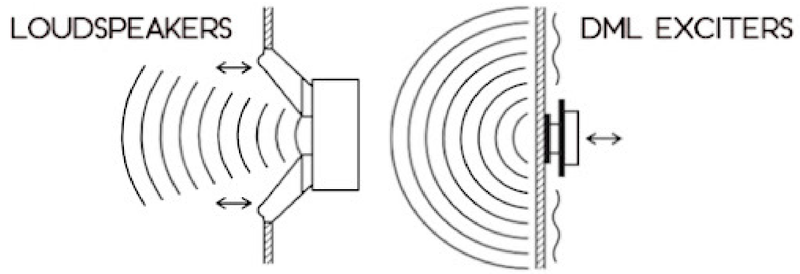


Figure 36: Visual representation of the sound dispersion from a regular cone speaker and a DML (About DML Exciters, n.d.).

above 250Hz being affected by stiffness, density, internal damping, cell structure (for foam materials) and the compression (bulk) modulus. Examples of DMLs made from composite sandwich panels, balsa- and spruce wood laminates, expanded polystyrene and other foam panels are known (Canton, 2018; DML500 Distributed Mode Speaker, n.d.; Luo, 2011).

The benefits of a DML versus a traditional speaker are:

- High sensitivity (power input versus output loudness)
- Flat panels can be integrated into architectural elements to be hidden from sight
- High dispersion, low directivity of sound that is not affected by the size of the panel
- Bipolar output, on the front and back side of the panel, this limits interactions with side walls.
- Diffuse output allows a DML to fill a room with highly even sound coverage.

The disadvantages of a DML versus a traditional speaker are:

- Large frontal surface area.
- Limited low end frequency response.
- Frequency output is uneven, with output peaks in the high frequencies.
- High sound dispersion can limit stereo effect when listening from far away.

To verify if WTBM panels are suitable for use in a DML application, additional research is necessary.

SPECIFIC ACOUSTIC APPLICATION – TONE BOARD

Picea Sitchensis is one of the materials found during the direct substitution selection phase of CATSS which indicates that its material properties are highly similar to those of WTB sandwich panels. According to the London Guitar Studio (n.d.) acoustic instruments with toneboards made out of Sitka Spruce have a desireable sound, since their materials have a high velocity of sound. An example of the construction of an acoustic guitar can be seen in Figure 37. Sitka Spruce is also extensively used in the tone boards of Yamaha's grand pianos (see figure 38) for its excellent tonal properties (How a Piano Is Made, n.d.).

Some advantages can be gained by incorporating WTB composites in the construction of acoustic instruments:

- They can withstand temperature and moisture changes, resulting in lower maintenance and tuning efforts.
- The material has a high stiffness and yield strength, meaning the high forces resulting from string tension can be loaded directly onto the body of a string instrument, requiring less heavy and expensive reinforcements.

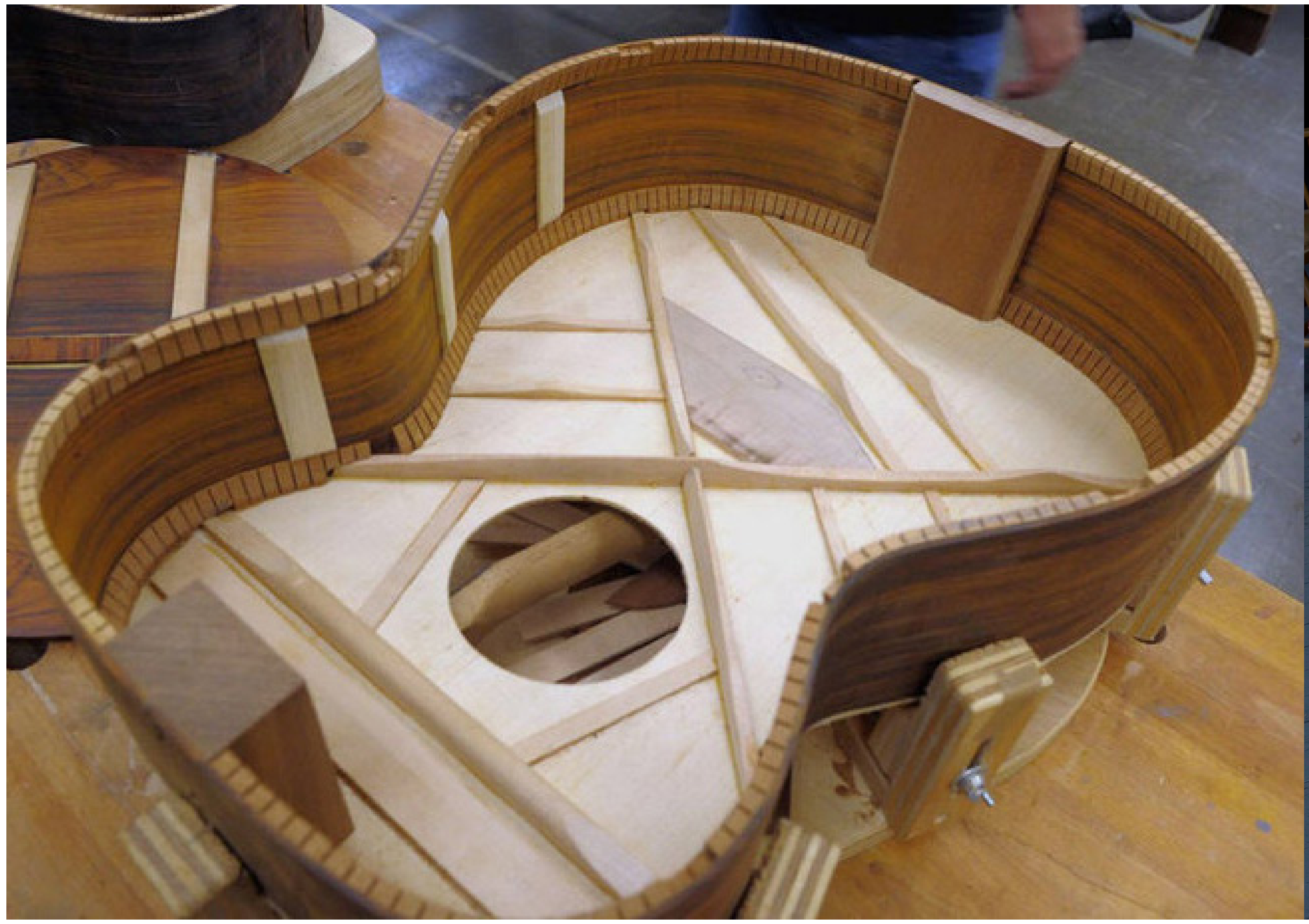


Figure 37: The body of an acoustic guitar with the top panel, also known as the tone board, being constructed from Sitka Spruce (Glen, 2016).

Figure 38: Grand piano soundboard made from spruce (Steinway B Sound Board Project, n.d.)

MEASURING ACOUSTIC PROPERTIES

Since little is known about acoustic properties of WTBM, measurements need to be conducted to find these relevant acoustic properties of WTBM.

Three tests were conducted:

1. Damping coefficient test using an impedance tube
2. Transmission loss test in a custom test setup
3. DML application test in a custom test setup

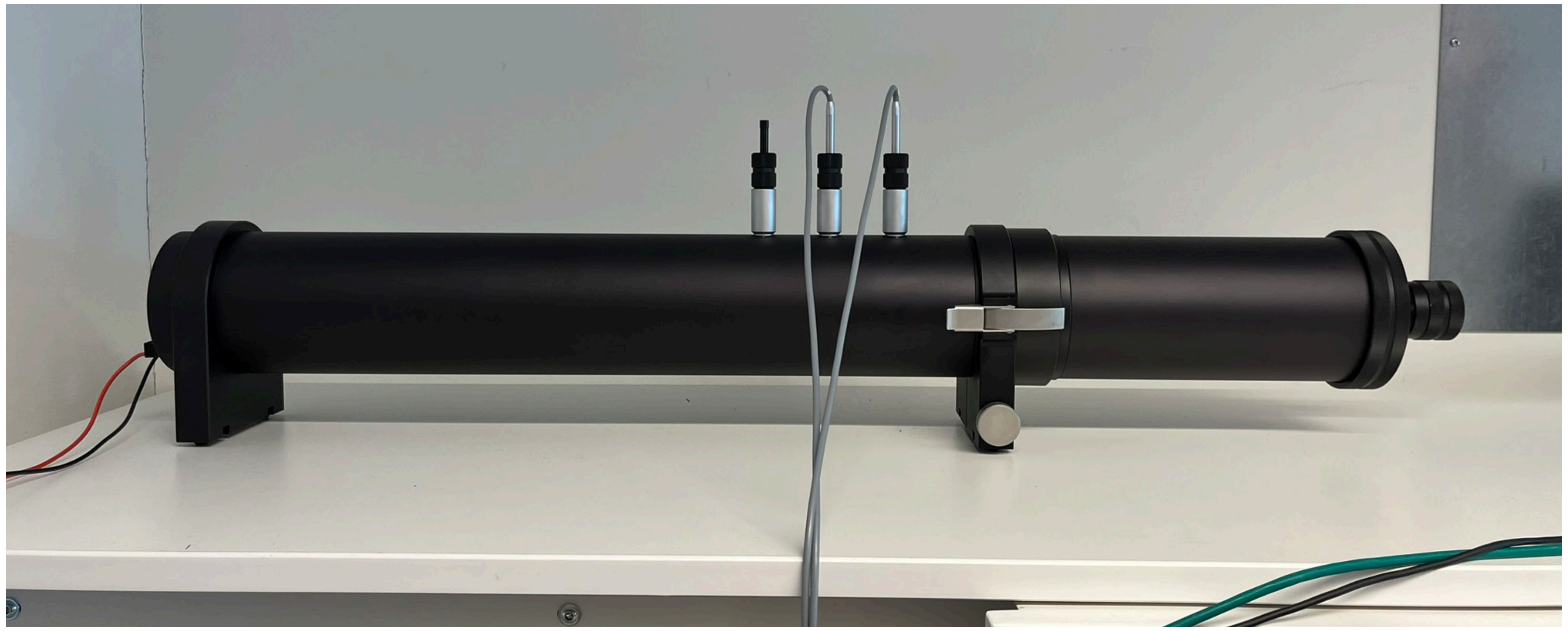


Figure 39: Impedance tube measuring device.

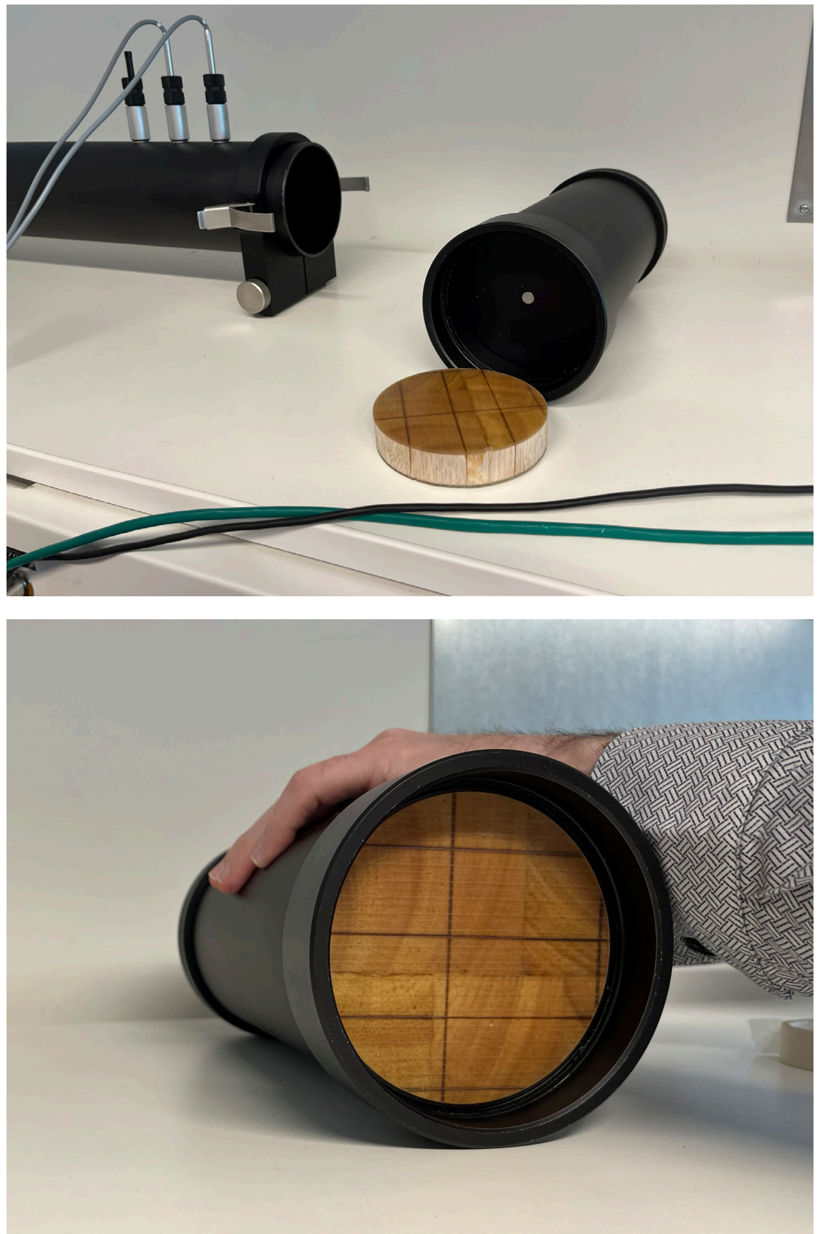


Figure 40: Circular material sample loaded into the impedance tube.

DAMPING COEFFICIENT

Since the CATSS method identified many applications reliant on the acoustic damping property of the material, and little data on it is available, measuring this property is of value. To measure the damping coefficient of WTBM, an instrument called an impedance tube is used to test a small sample of material (see figure 39).

Here, a calibrated speaker is situated at one end of an aluminum tube with an internal diameter of 100 mm, with the material sample placed in a piston-like holding device at the other. Two microphones are situated at a known distance in the tube. Broad spectrum white noise is played into the tube and the sound pressure level (SPL) of each frequency is then picked up by the microphones. The damping coefficient can be calculated from the difference in SPL between the initial sound wave and the reflected sound wave travelling back past the microphones in the reverse direction.

RESULTS - DAMPING COEFFICIENT

The sample that was initially tested was a composite sandwich consisting of 1,5 mm GF, 18 mm balsa wood, 1,5 mm GF which was loaded into the impedance tube (see Figure 40). The results of this test can be seen in Figure 41. Here, “0” means no sound is absorbed, while “1” means all sound is absorbed.

CONCLUSION – DAMPING COEFFICIENT

The sound absorption coefficient of the panel is rather low, with all frequencies experiencing an absorption of less than 0,2 (the initial part of the measurement is inaccurate due to limitations of the test setup). This means WTBM likely is not suited for sound absorbing applications.

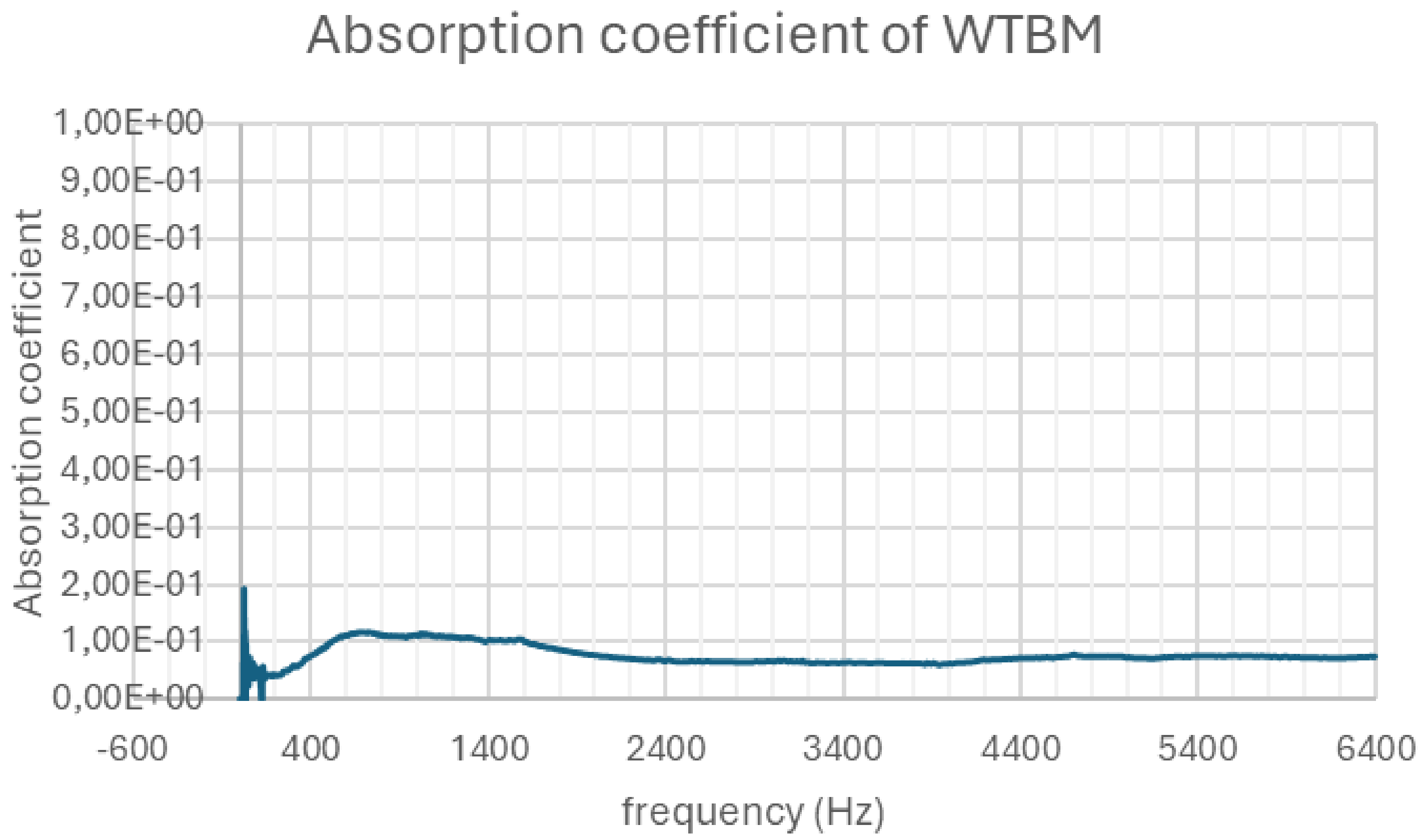


Figure 41: Sound absorption coefficient per frequency for a WTBM GF-balsa sandwich panel.

MEASUREMENT OF TRANSMISSION LOSS

Since CATSS identified a number of applications that rely on sound insulation, material properties related to this metric need to be investigated. Many of the acoustic properties identified earlier (see Table 3) require highly specialized and complex equipment to be measured. Due to the time constraints and limited availability of WTBM for this project, a feasible yet relevant material property needed to be selected for measurement.

An acoustic material property that was found feasible and relevant for this project is the transmission loss (TL), or the level of sound that is prohibited from passing through a material. There is hardly any data available on the TL of composite materials, and measuring the transmission factor of a DWBM panel is possible within the scope of the project.

Various methods for measuring TL are known. The impedance tube shown earlier can be modified to carry out such a test. However, according to Collings and Steward (2011) this test has the downside of having a limited frequency range in which the test is accurate. Next to this, Caballol and Raposo (2018) say that the variability of obtained TL data between four different tube sealing methods was very high and the method is therefore not suited for highly rigid materials. A large-scale test produces data covering a wider frequency range that is less sensitive to boundary conditions and can be done using multiple angles of incidence, if desired. The measurement that was performed during this MSc project was based on an adapted version of the two-room method as described in ASTM E90-09 (2016).

TEST SETUP IN ANECHOIC CHAMBER

To properly test acoustic properties, a suitable experimental environment is necessary. The TU Delft has a special anechoic chamber, a room with a low noise floor and virtually no sound reflection from the walls. The anechoic chamber is located in the Faculty of Applied Sciences and features large glass wool cones placed on the inner walls to absorb as much sound as possible (see Figure 42).

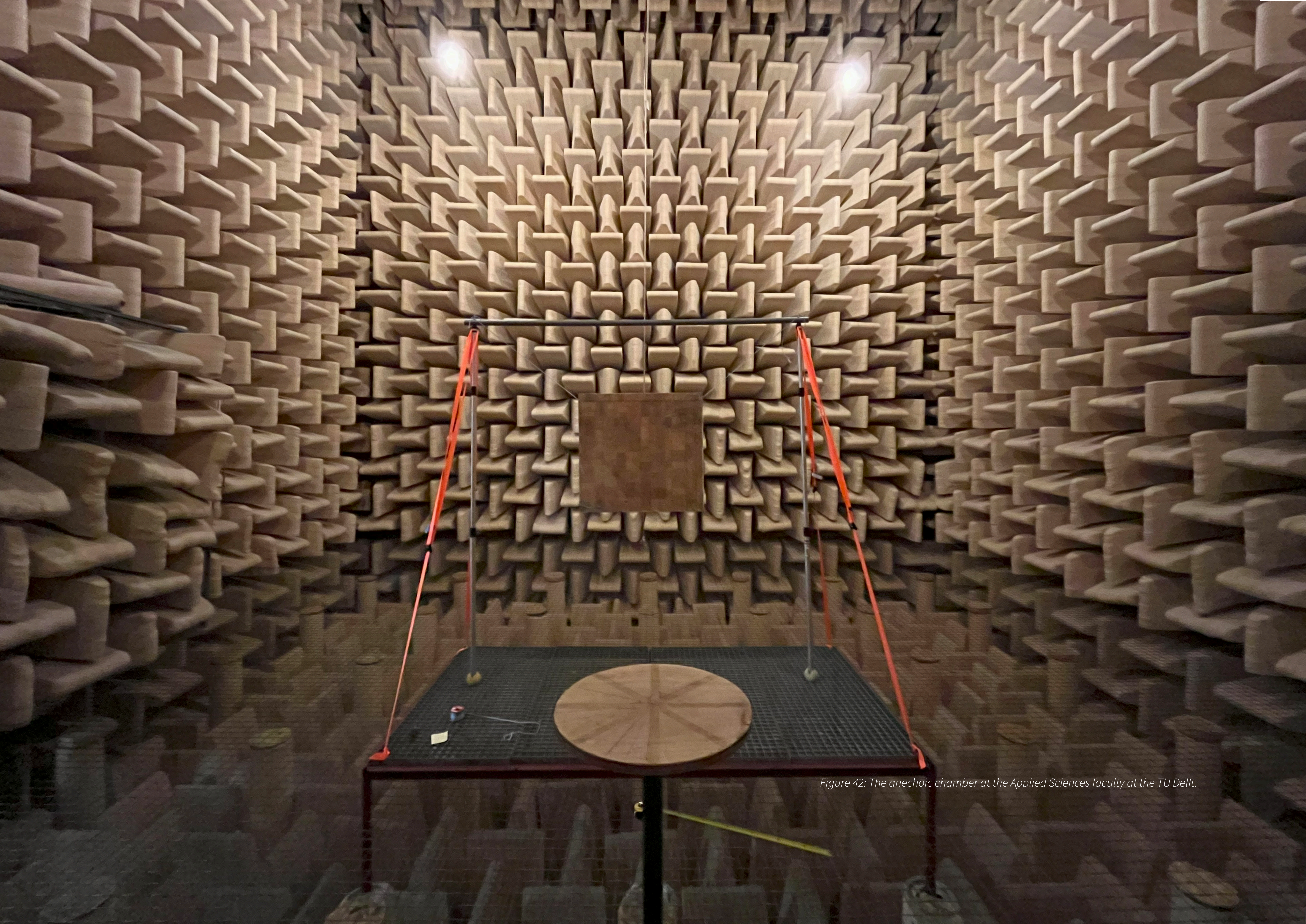


Figure 42: The anechoic chamber at the Applied Sciences faculty at the TU Delft.

At the anechoic chamber located in the Applied Physics faculty building, the test setup was constructed according to Figure 43 and 44.

The dampening foam used in this setup was “Flamex Basic” melamine acoustic foam with a thickness of 50mm. The test sample was a section of GF balsa composite panel from a decommissioned WTB. The microphones, microphone interface and recording software were provided by the faculty of Aerospace Engineering.

Distance L1 (Figure 44) depends on the placement possibilities of the speaker plateau and the test setup plateau (a grid with placement options is present in the anechoic chamber). The distance L2 was set at 1 m and could easily be varied.

An overview of the setup inside the anechoic chamber can be seen in Figure 45.

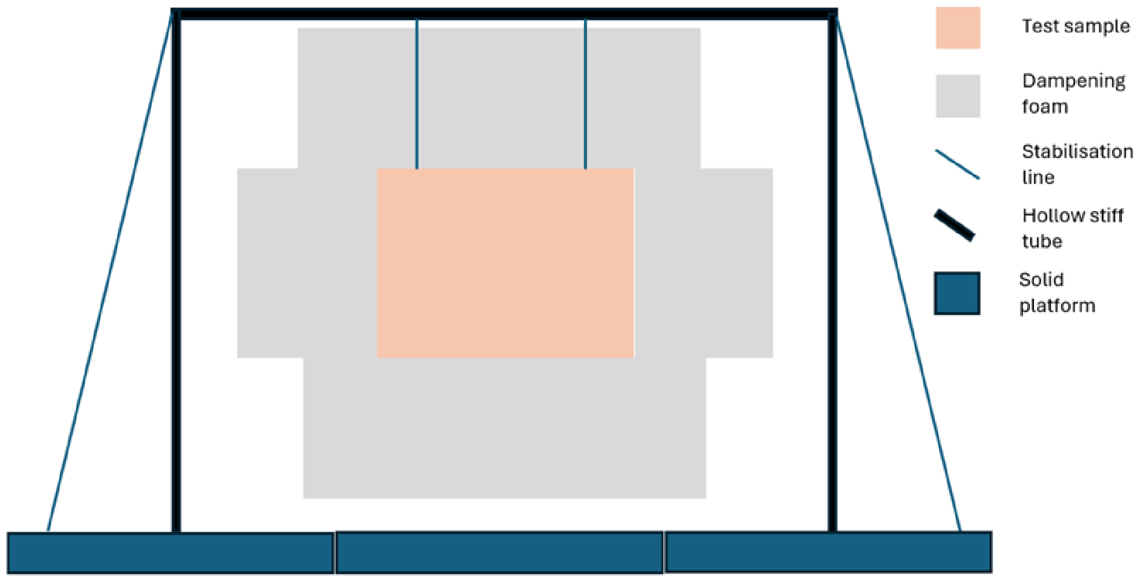


Figure 43: Front view diagram of test setup 1.

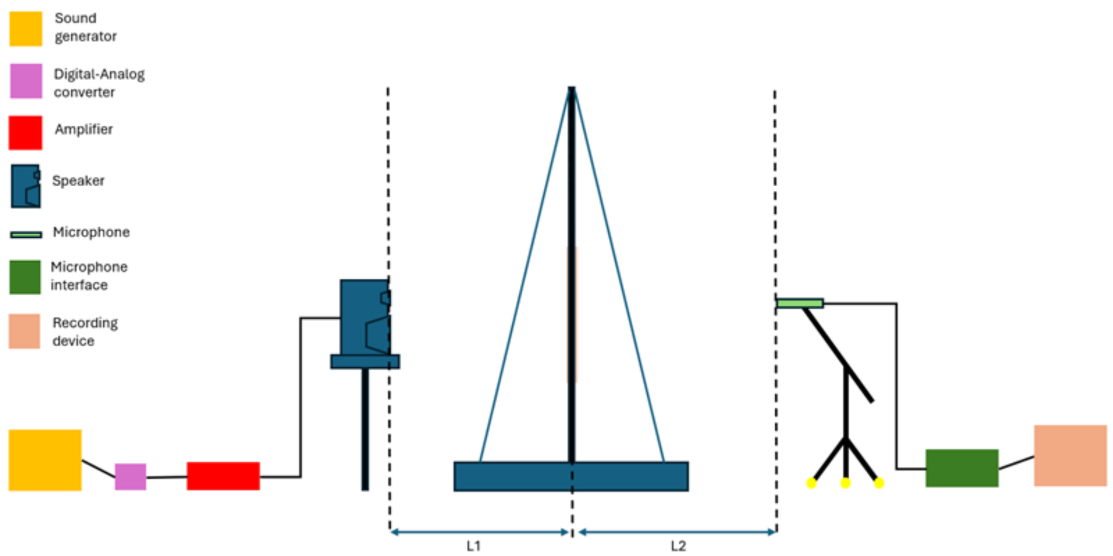


Figure 44: A diagram presenting a side view of test setup 1 with the test panel in the middle.

Figure 45: Test setup 1 with microphones and speakers in place.

TEST METHOD

Once the test setup was constructed, the Transmission Loss (TL) of wind turbine blade material could be measured.

The TL test was comprised of four separate tests:

- BL1: a baseline test to measure the direct output of the sound source.
- TLF: transmission loss "front" test that was performed with the WTBM panel installed with its first (front) side towards the sound source.
- TLB: transmission loss "back" test that was performed with the same WTBM panel that was placed with its second (back) side to the sound source.
- TLR: transmission loss "reference" test performed with a reference material in the form of a melamine absorption panel that was placed in the measuring setup.

All measurements were done twice with two volume settings of the amplifier driving the sound source; first with an indicated 50% volume and then with an indicated 75% volume. In total, six measurements with WTBM were taken, but only the measurements with 75% output were used to analyze data, since they had the best signal to noise potential.

Baseline measurement 1 (BL1)

To perform a baseline measurement, an unobstructed path between the speaker and the microphone needed to be assured in the test setup (see Figure 46).
To measure the average SPL across all relevant frequencies

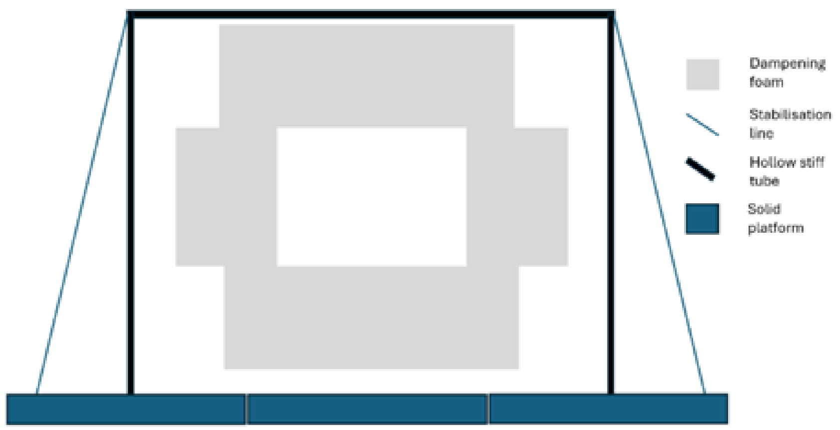


Figure 46: Diagram presenting front view of test setup without test panel.

in the sound field behind the test setup, three multiple microphones were placed inside the area where the measurements were made (M_{df}) (see Figure 47).

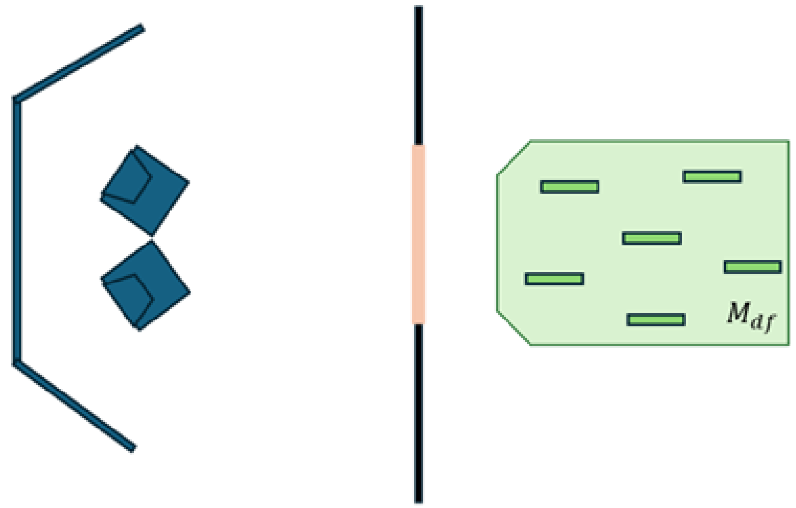


Figure 47: Diagram presenting top view of test setup and multiple microphone placements inside measurement area M_{df}.

The measurement area was indicated with tape, as can be seen in Figure 48, where the indicated area represents the 'shadow' that the panel would create if the speaker setup would have been a point light source.

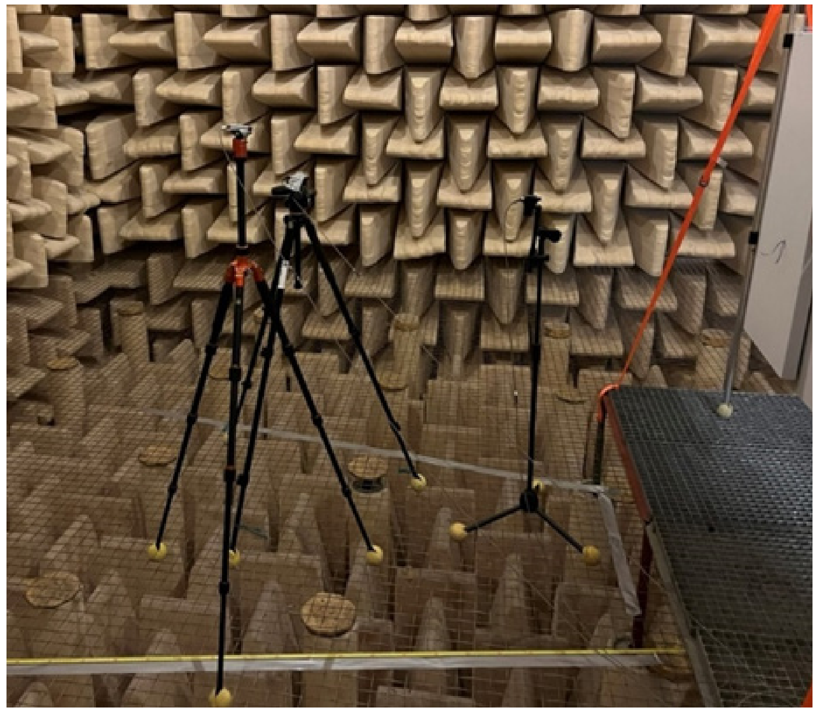


Figure 48: Three microphones placed on tripods within the indicated measurement area M_{df} behind the test panel.

Transmission Loss front (TLF)

The WTBM test panel was hung in between the speaker and the microphone. All other aspects of the test setup remained the same as in the case of test BL1. Test signal 1 was played and recorded at the same measurement locations as BL1 to obtain the SPL created by the wideband white noise signal.

Transmission loss back (TLB)

To adhere to the specifications of ASTM E90-09(2016) as much as possible, the test as described in TLF should be carried out in the opposite direction, changing the side of the test panel that faces the sound source. This way, the results of test TLF can be verified with a second test and any variance can be averaged out. The WTBM test panel was put in place with its second, opposite side facing the sound source, after which the same set of measurements as in TLF in area M_{df} were performed. The rest of the setup remained identical to test TLF.

Transmission loss reference (TLR)

To evaluate the accuracy of the measurement method, a reference material was measured to compare the found values to those known from literature. The measured reference material was a melamine foam “Flamex Basic” panel, which was placed in the opening instead of the WTBM panel (as seen in Figure 50).

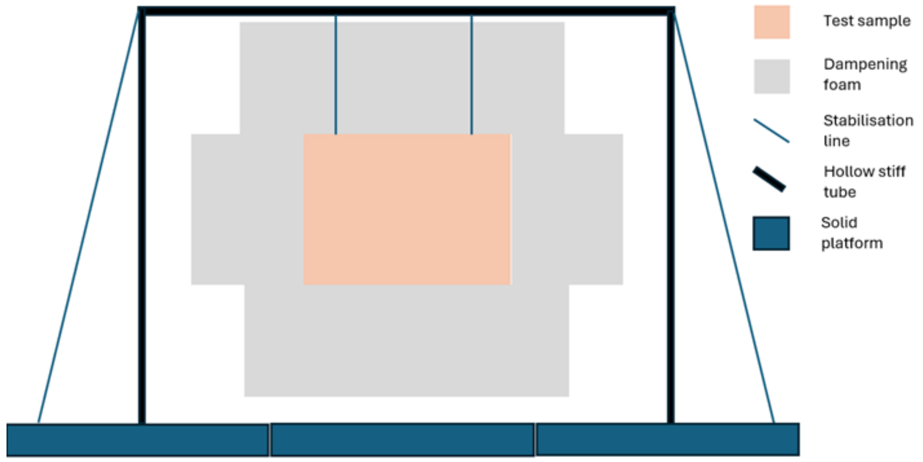


Figure 49: Diagram presenting front view of test setup with WTBM test panel (test sample) installed.

Figure 50: Test setup with a reference material (Flamex basic acoustic foam).

RESULTS

According to ASTM E90-09(2016), the TL at each frequency f can then be determined using the following formula:

$$TL_{WTBM} (f) = L_{BL1} (f) - L_{TLA} (f) + 10logS/A_R (f)$$

Where:

$TL_{WTBM} (f)$	= TL of the WTBM panel [dB]
$L_{BL1} (f)$	= average SPL in measurement BL1 [dB]
$L_{TLA} (f)$	= average SPL from measurement TLF and TLB [dB]
S	= area of test panel [m^2]
$A_R (f)$	= sound absorption of measurement room [m^2]

Since the test setup differs from the description given in ASTM E90-09(2016), the calculation for the TL was altered. The measurement conditions between BL1, TLF and TLB were identical. Next to this, there were no two distinctly separated volumes in which the sound source and measurement equipment were housed. Therefore, the sound absorption of the measurement room and the panel area are not applicable. The TL at each frequency can be calculated using the simplified formulas:

$$TL_F (f) = L_{BL1} (f) - L_{TLF} (f)$$

and

$$TL_B (f) = L_{BL1} (f) - L_{TLB} (f)$$

Where:

$TL_F (f)$	= transmission loss calculated from TLF [dB]
$TL_B (f)$	= transmission loss calculated from TLB [dB]
$L_{BL1} (f)$	= average SPL in measurement BL1 [dB]
$L_{TLF} (f)$	= average SPL in measurement TLF [dB]
$L_{TLB} (f)$	= average SPL in measurement TLB [dB]

To get the average transmission loss TL_{avg} at each frequency f the following formula was used:

$$TL_{avg} (f) = (TL_F (f) + TL_B (f)) / 2$$

Using Microsoft Excel, the data obtained during BL1, TLF, TLB and TLR tests was processed and graphed. The resulting TL values for the WTBM panel and the “Flamex Basic” panel are presented in Figure 51.

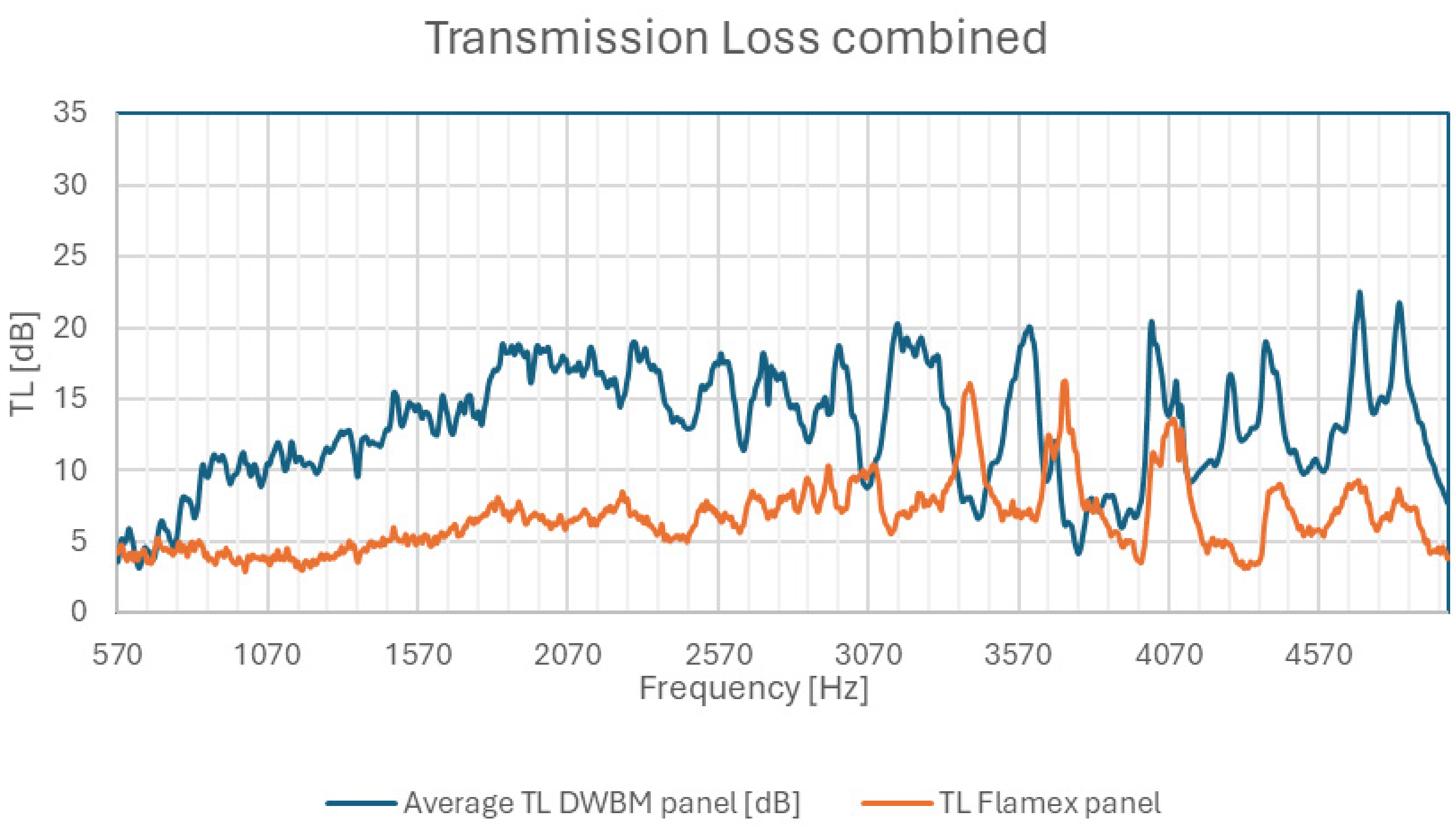


Figure 51: Scatter plot showing average TL of the DWBM panel and "Flamex Basic" (melamine foam) panel overlayed.

VERIFICATION

Before a conclusion can be drawn from the results, the results must be verified, since the measurement method was adapted from the standard. This verification was done in two ways, by:

1. Measuring a calibration panel with known TL characteristics.
2. Comparing measured TL of WTBM with other materials.

Calibration panel with reference material

The "Flamex basic" panel was tested to calibrate the measurement method, since it is a material with well-known acoustic properties. Published TL data of melamine foam panels was used as a comparison to validate the accuracy of the WTBM TL measurements.

When comparing the TL values found in literature to the data retrieved from testing, the testing conditions need to be taken into consideration. When a sample is clamped on all sides such as in a test shown by Hughes et al. (2004) the

TL values are higher compared to those obtained when a looser friction fit is applied – such as in the impedance tube test shown by Zai et al. (2021). Taking this into account, the testing conditions (including constraints and panel thickness) during test conducted for this MSc project were most similar to those of Zai et al. (2004). Therefore, the test data from Zai et al. (2014) was compared to the field test data, where the field test TL data for the melamine foam panel ranged from 4 to 16 dB and that from Zai et al. (2004) from 6 to 10 dB (see Figure 52).

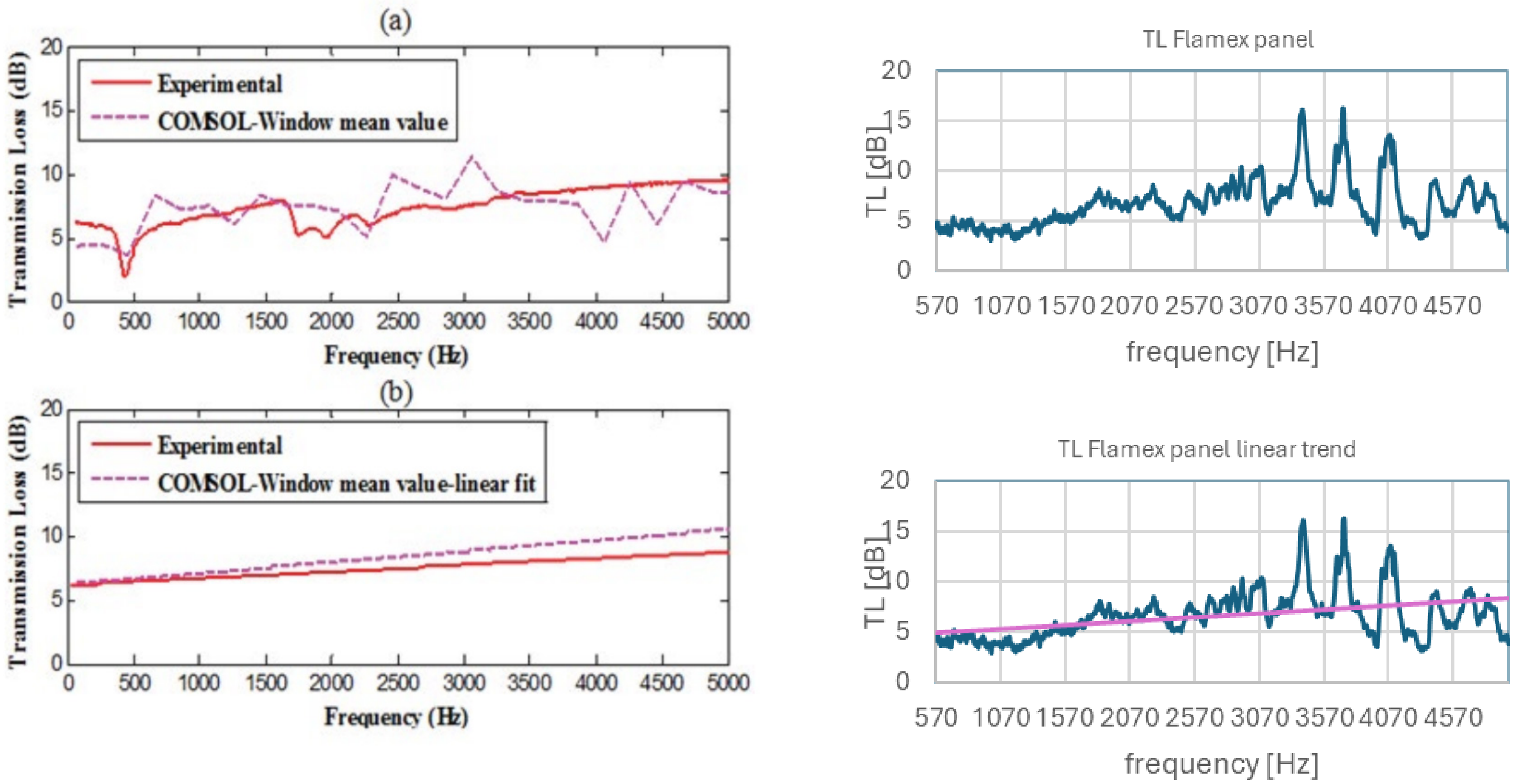


Figure 52: TL for a melamine foam panel measured with an impedance tube (top left (Zai et al., 2004)) and with the TLR measurement (top right). Bottom left shows a trend line of the TL measured in an impedance tube (Zai et al., 2004) which strongly overlaps with the trend line from the experimental TLR measurement shown in the bottom right.

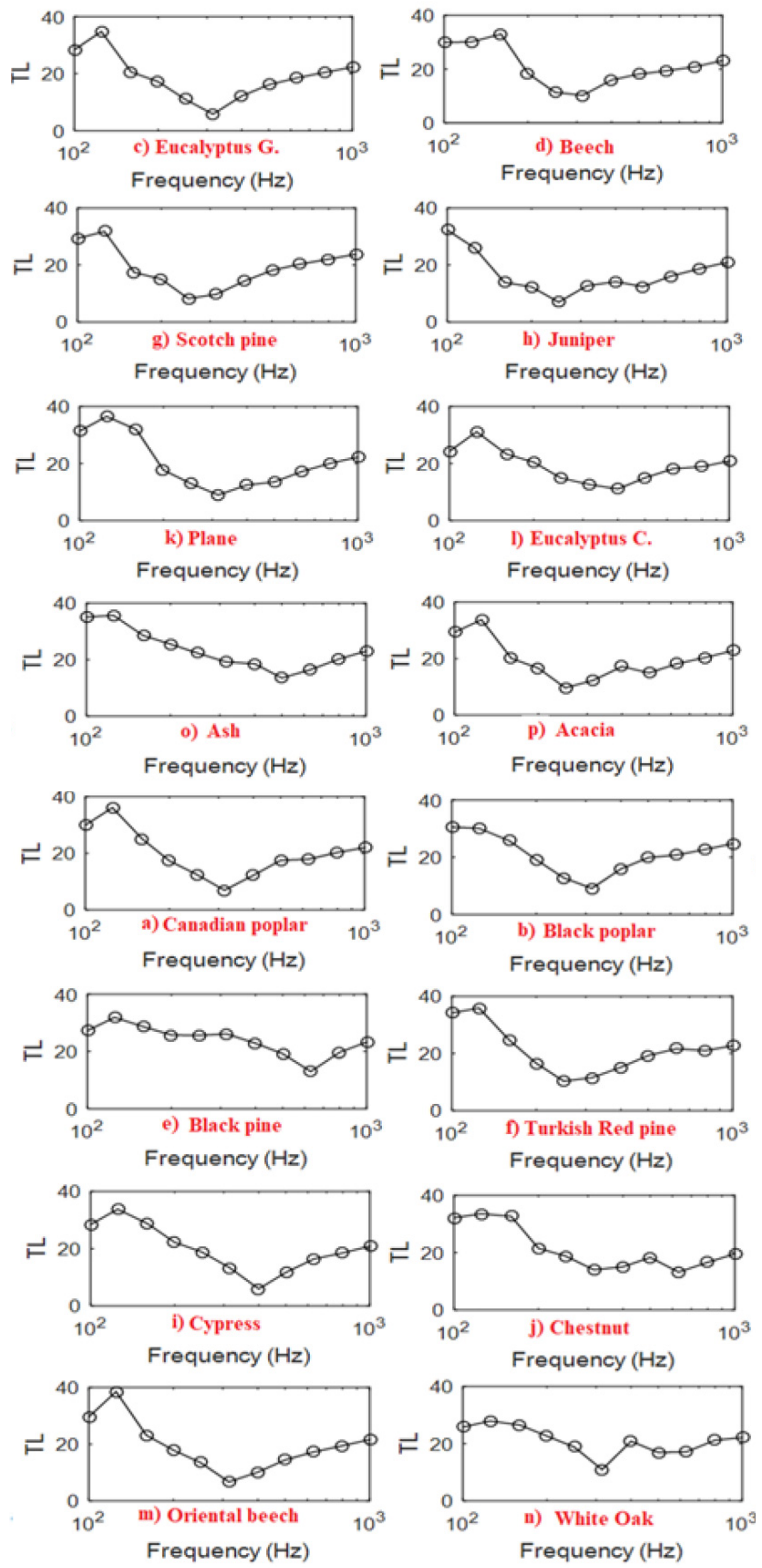


Figure 53: TL data from multiple wood samples (Çavuş & Kara, 2020).

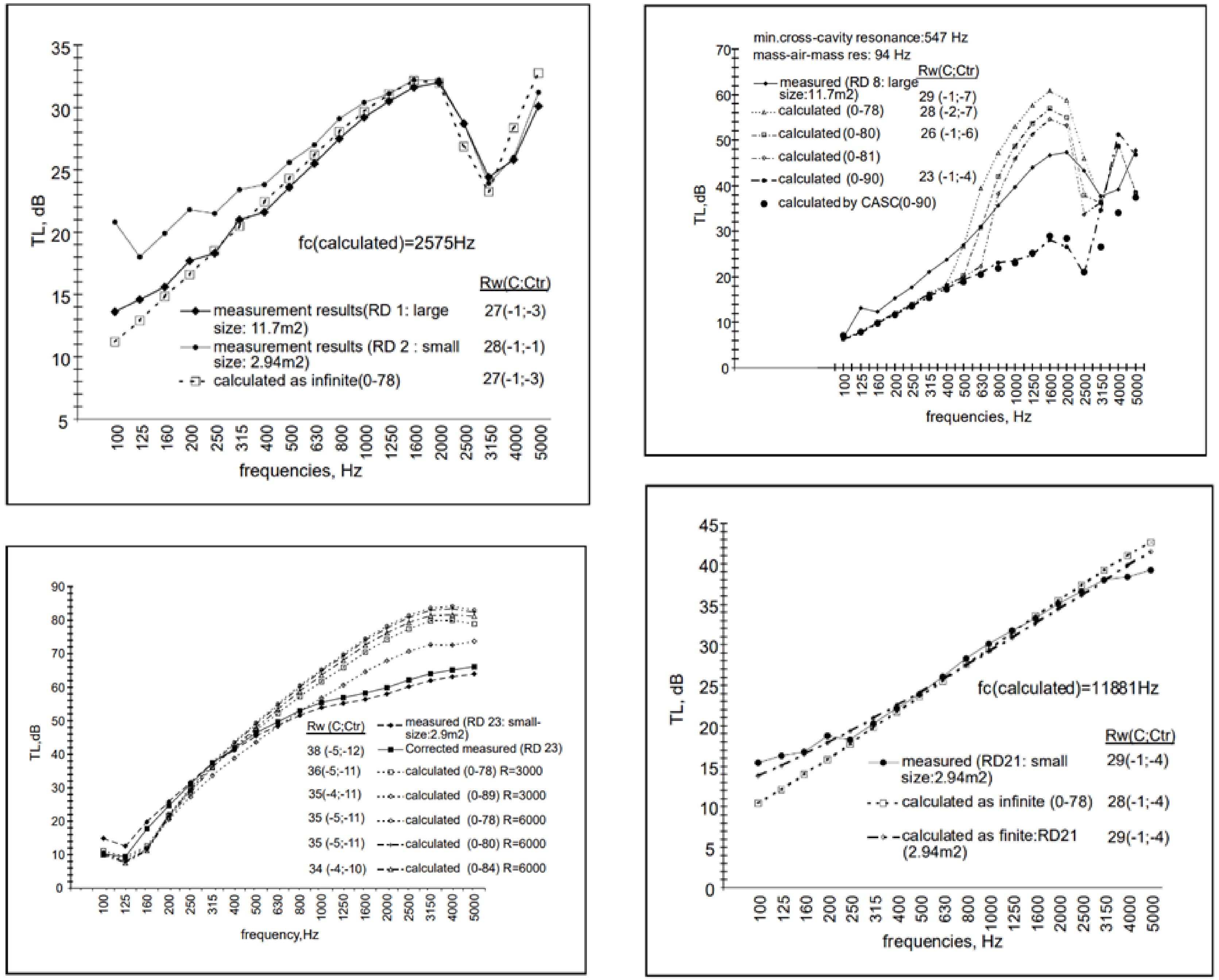
There is a significant difference between the two datasets. However, the difference occurs mostly in the spikes seen in the frequency range between 3300 and 4070 Hz. The trend lines (see Figure 52, bottom right) are very similar, thus it can be assumed that the field test setup is valid, and its measurements results can be trusted. However, the strong peaks and valleys in the results require further study to determine their origin and impact on result validity.

Comparison of verified TL with known material data

To use the gathered data for application finding, existing TL data on materials currently used in acoustic applications needs to be identified to compare against. Çavuş & Kara (2020) took samples from various tree species and formed highly controlled material samples from them. This was done by drying and accurately shaping the samples, after which the samples were tested using an impedance tube. Figure 53 shows the resulting TL data from various wood samples, which illustrates that the TL value in the lower frequencies of all samples is relatively high. This is normally not the case, since lower frequencies are not easily measured using the impedance tube method due to the air seal around solid sample being imperfect (Caballol & Raposo, 2018). Thus, these high TL levels at low frequencies indicate a faulty seal and are therefore possibly inaccurate. Therefore, the frequency range that was used for comparison was 570 to 1000Hz, since the WTBM TL data starts at 570 Hz and the TL data from Figure 53 ends at 1000Hz.

The results presented in Figure 53 show similarities in TL for all tree species, with most of the compared frequency range indicating a TL of between 5 and 20 dB. The TL value for WTBM between 570 and 1000 Hz varies from roughly 5 to 13 dB. Interestingly, most graphs in Figure 53 show an almost linear increase in TL from 500-1000 Hz. The TL of WTBM shows a similar increase in this frequency region.
Figure 54 (top left) shows the measured TL of a single layer of gypsum board and a steel plate (Kurra & Arditi, 2001).

The TL measurements from multi layered panels are considerably higher than the WTBM measurements, whereas the single gypsum board comes closer to the WTBM measurements but is still considerably higher. However, all these panel materials have much higher densities when compared to the WTBM. The measured gypsum board has a density of 625kg/m^3, the steel panel a density of 7178kg/m^3 and the two multilayered samples higher still. WTBM sandwich panel has a density of 448-507kg/m^3 which is quite low when compared to the TL measurements. These materials were chosen because they are among the few materials that had accurate TL measurements available and are most similar in terms of thickness. Other materials include air gapped, multi layered steel wall sections with even higher densities.



CONCLUSION

The TL of WTBM sandwich panel is low when compared to other materials; however, considering its much lower density, its TL is reasonably high. This indicates an opportunity for applications that require a specific frequency range of sound isolation and a lightweight construction. Compared to many other materials, the TL measurement curve is low between 570 and 800Hz and highly uneven between 3000 and 5000Hz, indicating an opportunity for applications in which certain frequencies need to be blocked but others less so.

Figure 54: TL for a single gypsum board (first), a double gypsum wall with a 10cm air gap (second), a steel plate (fourth) and a double steel plate with 5cm glass wool in between (Kurra & Arditi, 2001).

DISTRIBUTED MODE LOUDSPEAKER (DML) TEST

To evaluate if DWBM is suitable for the acoustic application of sound generation in the form of a DML, a test setup was constructed in the anechoic chamber using WTB sandwich panels. First, an off-axis response test (DMLOAR) was done to measure the dispersion of the sound produced by the DML speaker. Secondly, a musical experience test (DMLMEX) was done to qualitatively measure the musical reproduction capabilities of the DML speakers. Combined, these two measurements aimed to find out whether WTBM is suited for the acoustic application of sound generation in the form of a DML speaker.

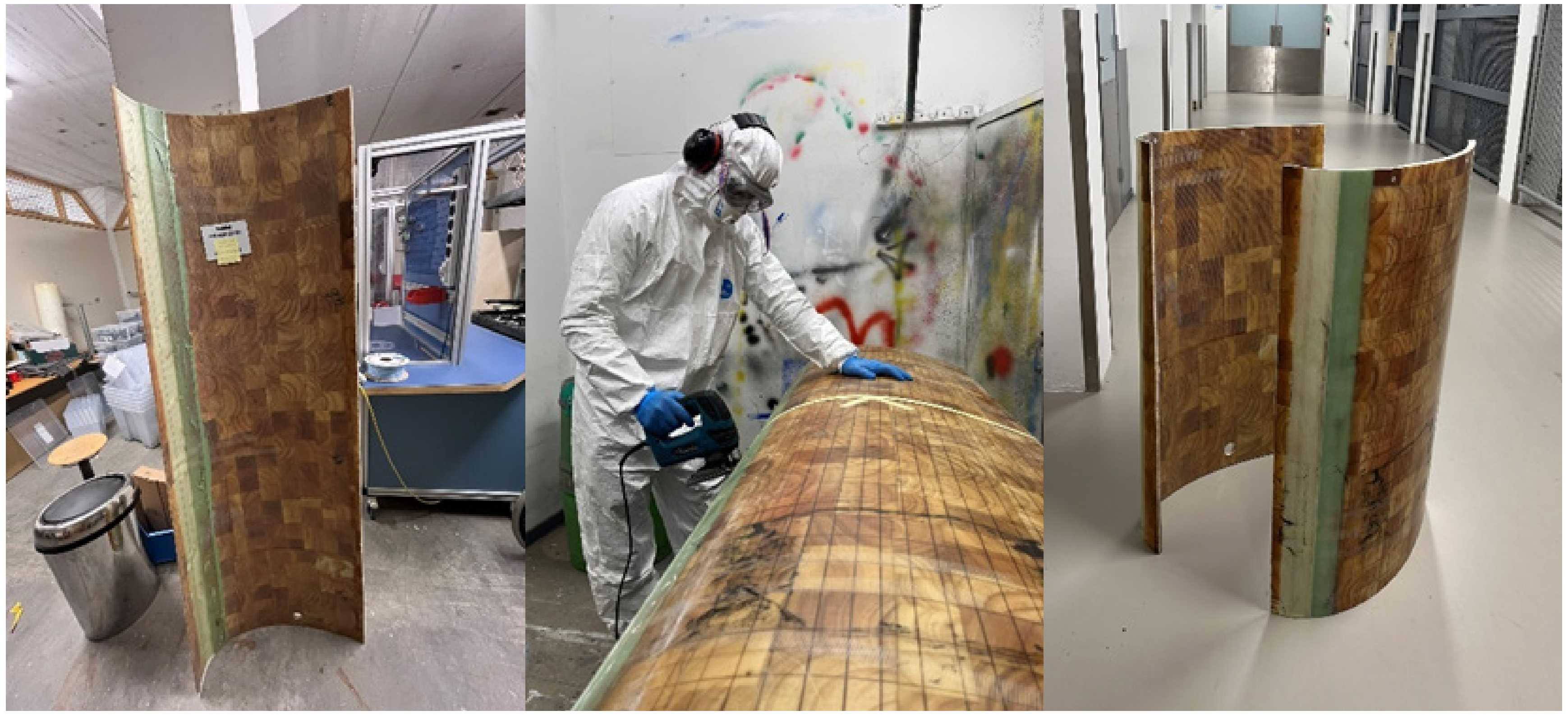


Figure 55: Taking a long section of WTBM and cutting it into two equal sections for the DML test.

DML PANEL CONSTRUCTION

The panels originated from an experimental WTB (see Figure 55). The panel was sawn into two equal parts.

Using these panels in combination with a set of exciters (see Figure 56), the WTBM panel was made to be able to vibrate using an audio signal through a speaker amplifier.

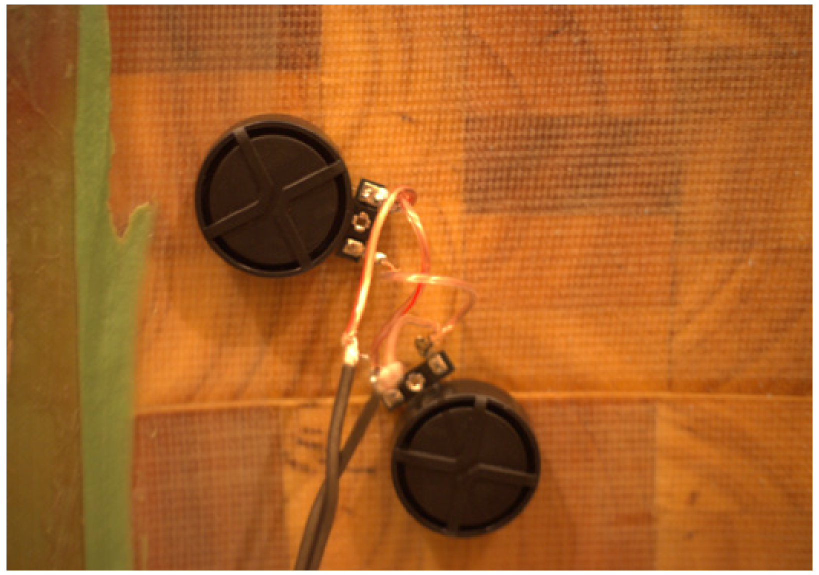


Figure 56: A set of exciters placed on the surface of one of the panels.

TEST SETUP (DMLOAR)

Two DML panels with exciters were suspended from the existing TL test setup, as seen in Figure 57. The panels were attached to and hung from the support structure using twine through holes in the top corners of the test panels.

The DML panels were measured with a microphone centered at L1=1 m distance in front of the right panel as shown in Figure 58.

The test setup in the anechoic environment can be seen in Figure 59.

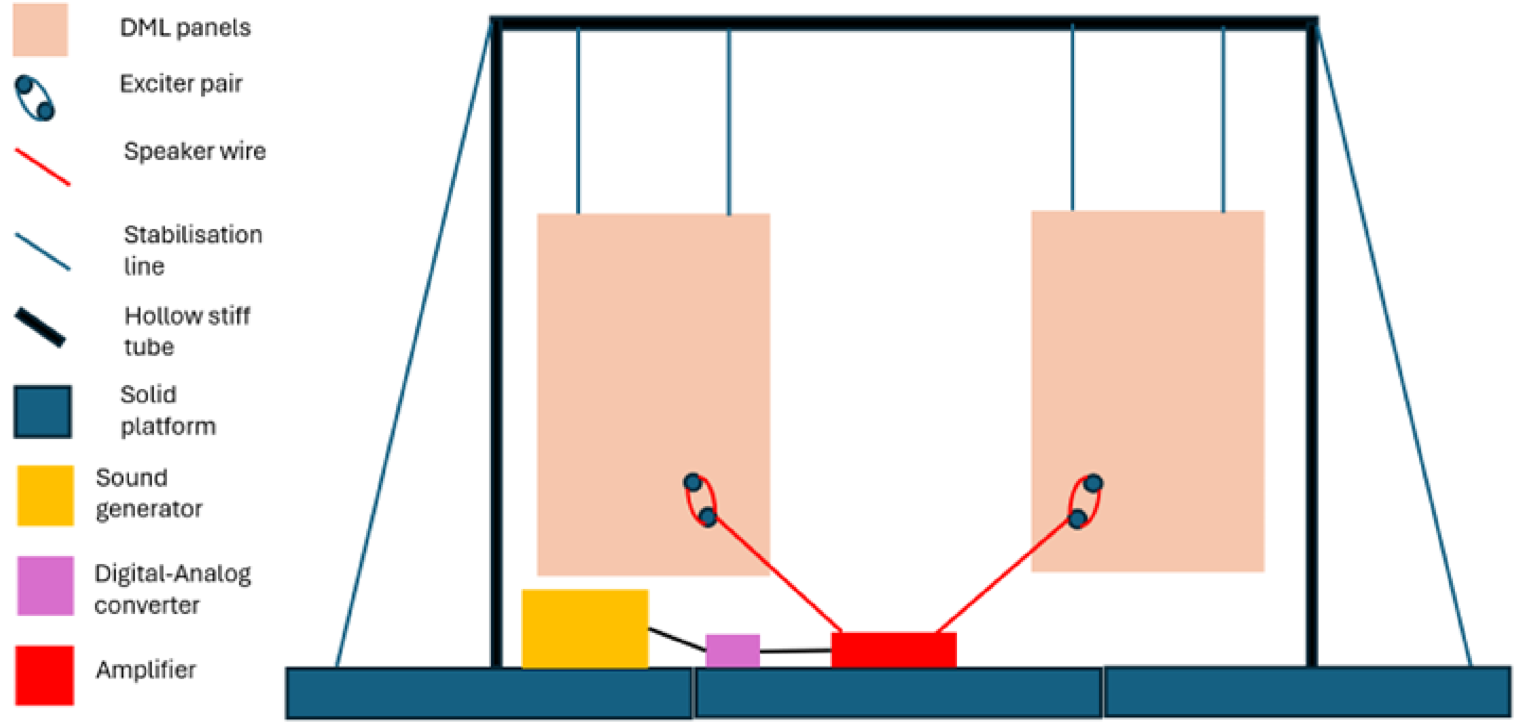


Figure 57: Diagram presenting the front view of DML test setup

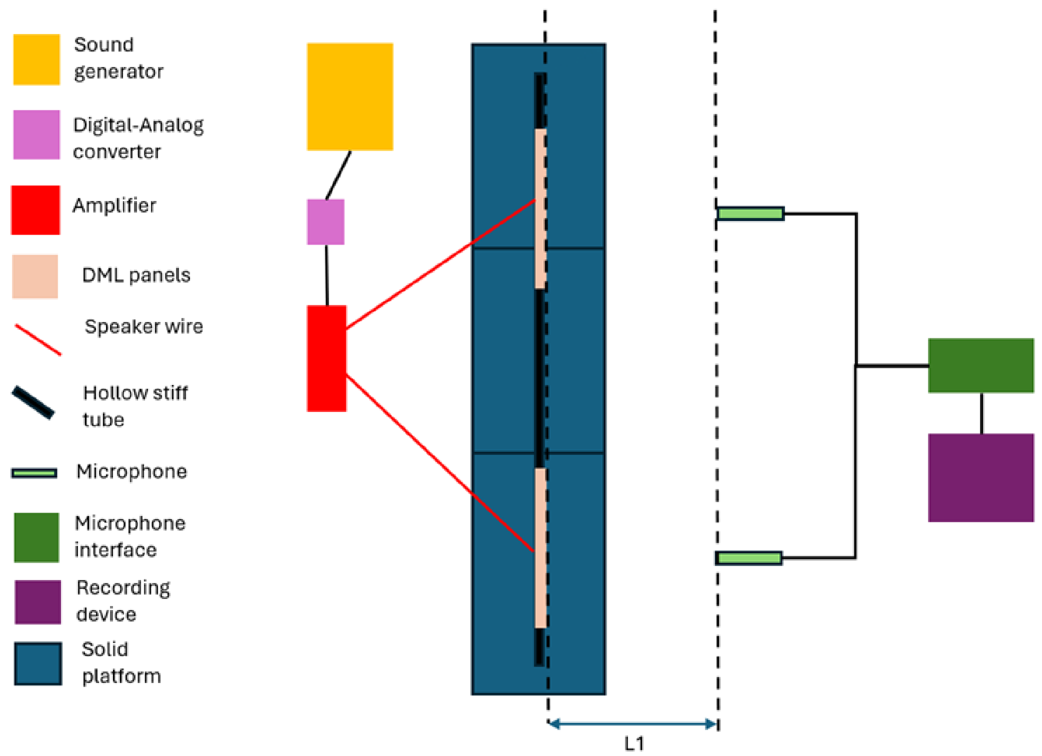


Figure 58: Diagram presenting a top view of DML test setup with microphone placement.

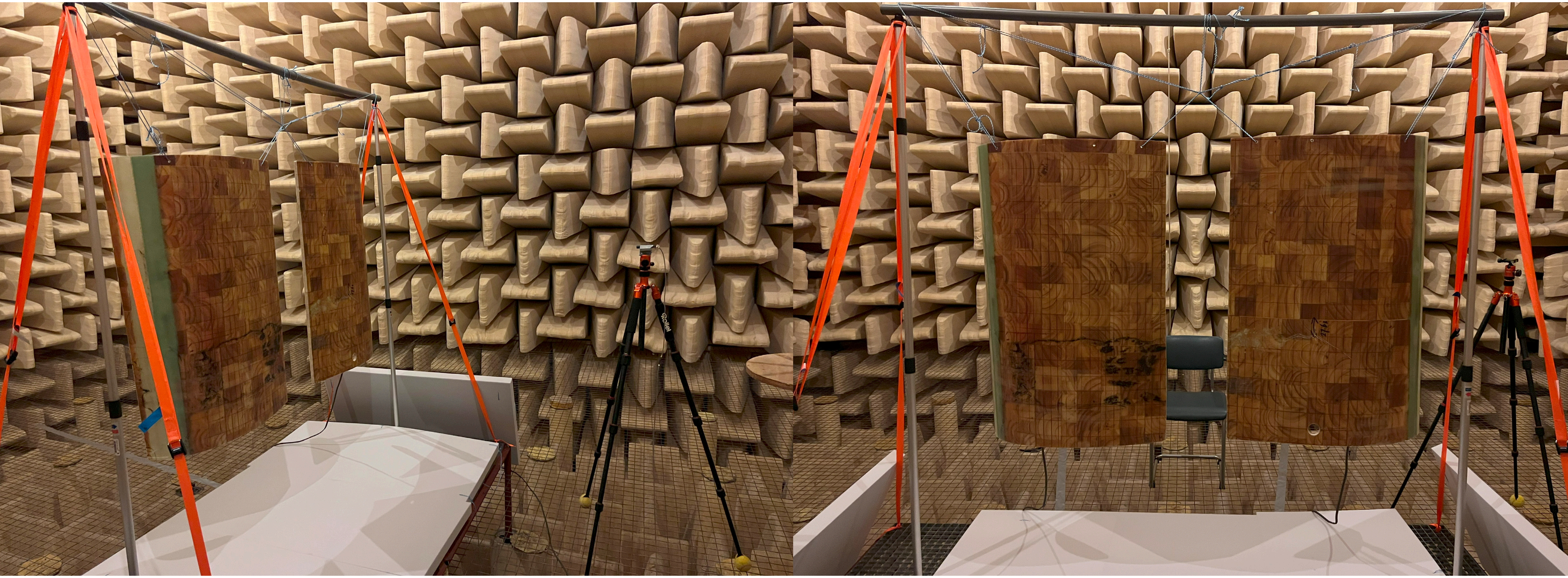


Figure 59: Two curved DWBM panels in a stereo configuration, ready to be measured.

DML off-axis response test (DMLOAR)

The off-axis response of the DML panels was measured using a microphone at a set distance from the center of the DML panel at various differing angles with increments of 22,5 degrees at 1 meter, as shown in Figure 60.

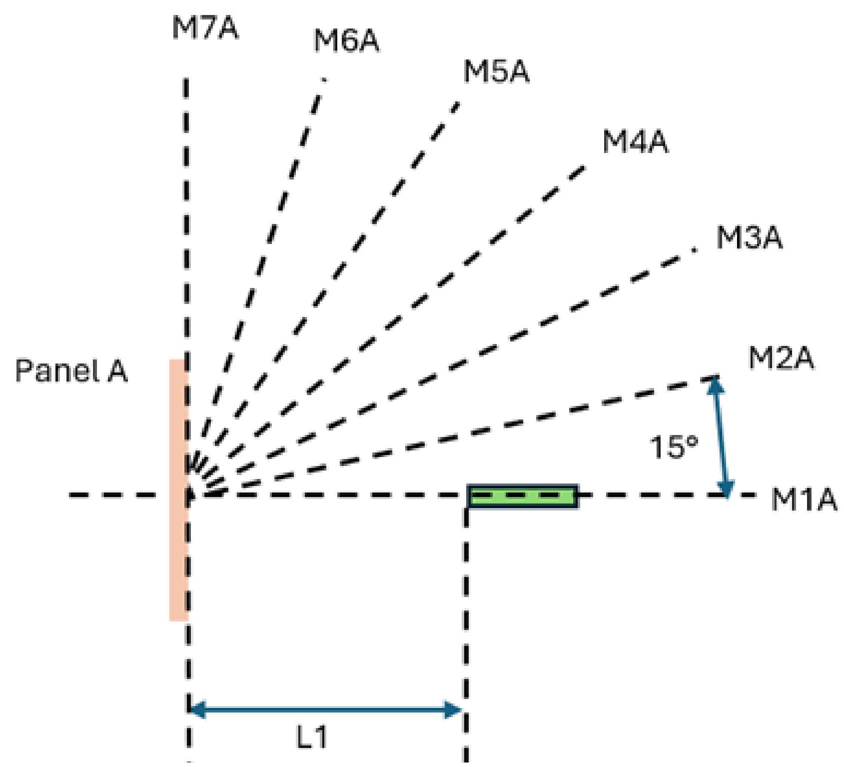
A frequency sweep from 80 Hz to 20 kHz was played through the DML and the SPL at each measurement point was recorded to compare against the on-axis response of microphone position M1A (as seen in Figure 60). An ideal off-axis response would show equal SPL across all microphone positions and across the complete frequency range.

Measurement results (DMLOAR)

The measurement data was processed to generate an SPL value in the frequency range from 80 Hz to 20 kHz, with steps of roughly 5 Hz. From this dataset, graphs were generated which can be seen in Figure 61.

Discussion (DMLOAR)

The data obtained from the DML off-axis response test shows a lot of variances, making it difficult to draw reliable conclusions. However, when looking at Figure 61 between 100Hz and 200Hz a large difference can be observed in the SPL between the 45 and 90 degrees offset measurements. Also, the 0 and 180 degree offset measurements generally have a much higher SPL across the complete measured frequency range when compared to the 90 and 45 degree offset measurements. This data coincides with personal and anecdotal experience during testing, therefore it can be said that the DML panel is strongly directional in its output. This will be discussed further in the chapter describing the DMLMEX test.



Conclusion (DMLOAR)

The test data shows the WTBM DML panel has a higher SPL when standing directly in front or behind the curved section of the panel and has a significantly lower SPL when standing at an angle of 45 or 90 degrees from the neutral position.

Figure 60: Top view of test setup for DMLOAR with microphone placements M: microphone.

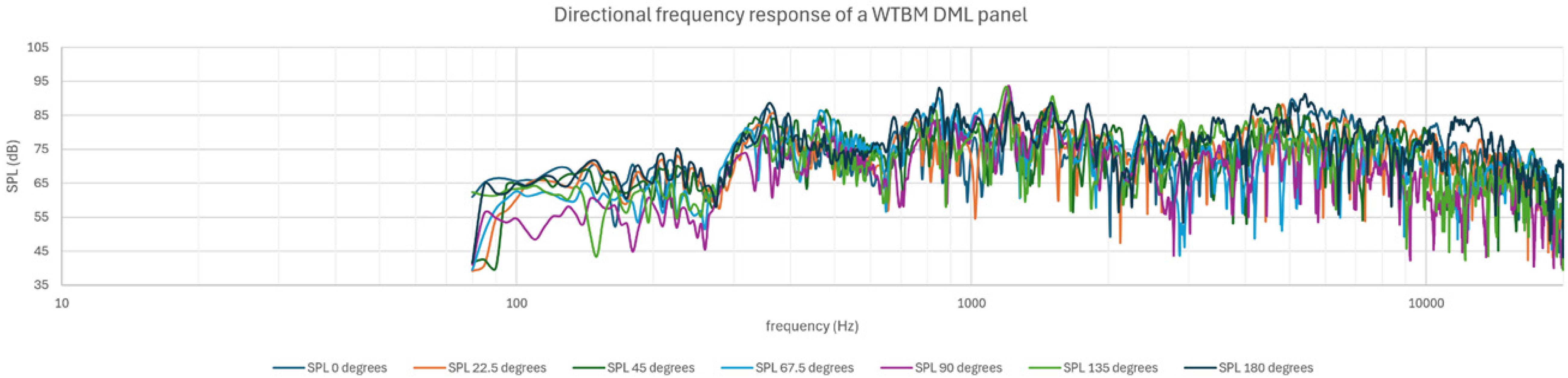


Figure 61: Off-axis frequency response curve of DML panel per offset.

DML MUSICAL EXPERIENCE TEST (DML-MEX)

To get a general overview of the capabilities of the DML panels to create an accurate and enjoyable music playback experience, the DMLMEX test was set up.

Test setup (DMLMEX)

The test setup, as shown in Figure 62, was without any recording equipment. Instead, a place for a listener ("listening position") in the middle between the two panels at a distance of roughly 2 meters was made.
DML panels A and B were hooked up to the right and left channel of a stereo speaker amplifier, respectively. Various listeners were placed at the listening position and a variety of music was played, while the researcher observed and made notes. The listener was encouraged to walk around the set of speakers during playback and was asked if there was any noticeable difference in the sound. In front and behind the center between the two panels, listening positions were marked to encourage the listener to try both locations. An example of a listening session is presented in Figure 63.

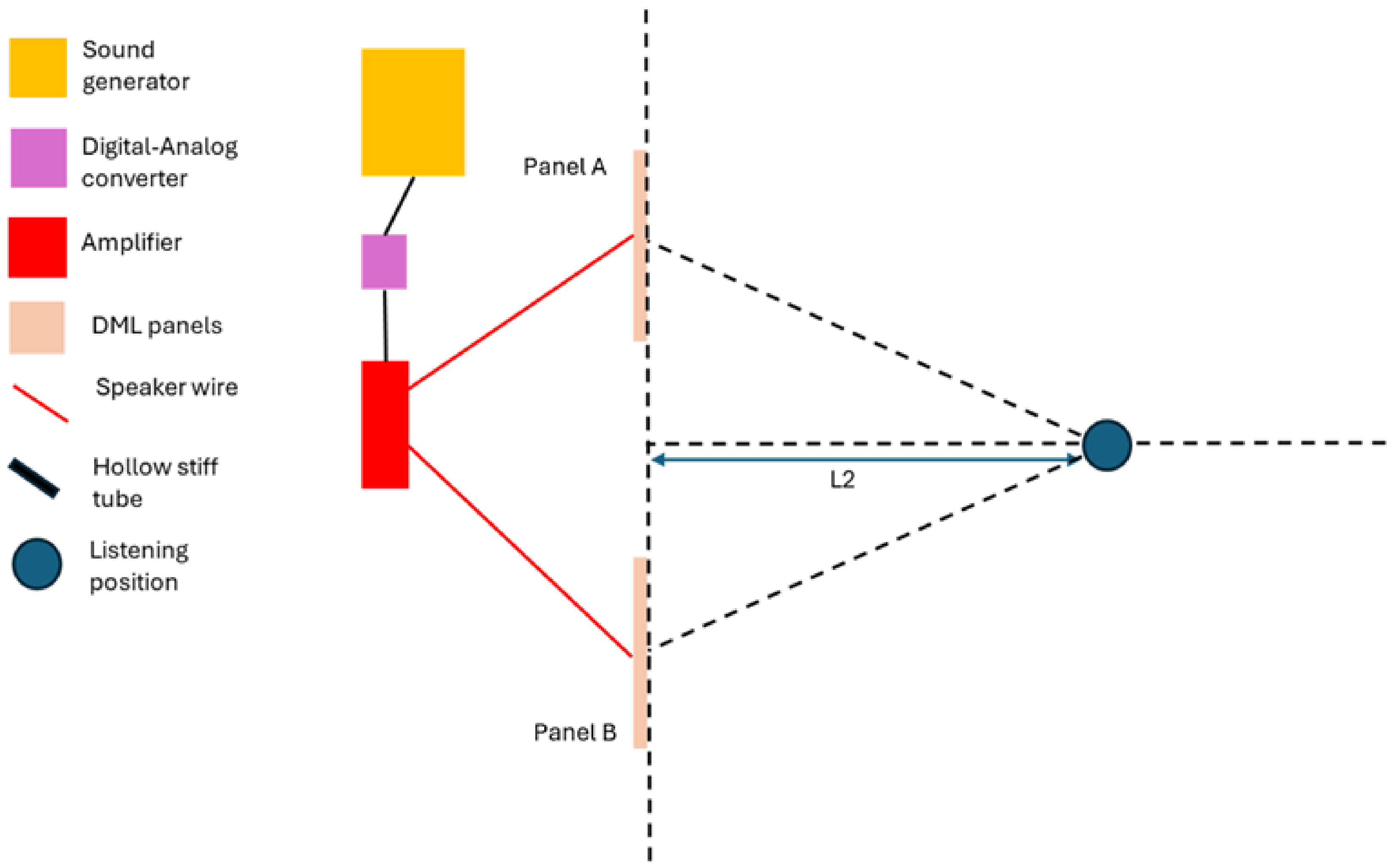


Figure 62: DMLMEX test setup diagram.

Measurement results (DMLMEX)

Responses to the DML setup were surprising. Listeners expressed that they had not expected the panels to produce such a convincing musical reproduction, especially when it comes to bass response:

- “It sounds so good!”
- “I cannot believe these things (the DML system) are making that sound!”
- “So, you have designed a HiFi system, when will they be available?”
- “Wow, it’s so weird to see nothing around that looks like it can make sound, but you can hear it so clearly, it is a bit freaky.”
- “How is it doing that?”
- “It feels like I am standing across from a wall made of sound.”
- “The voices sound a bit funny.”

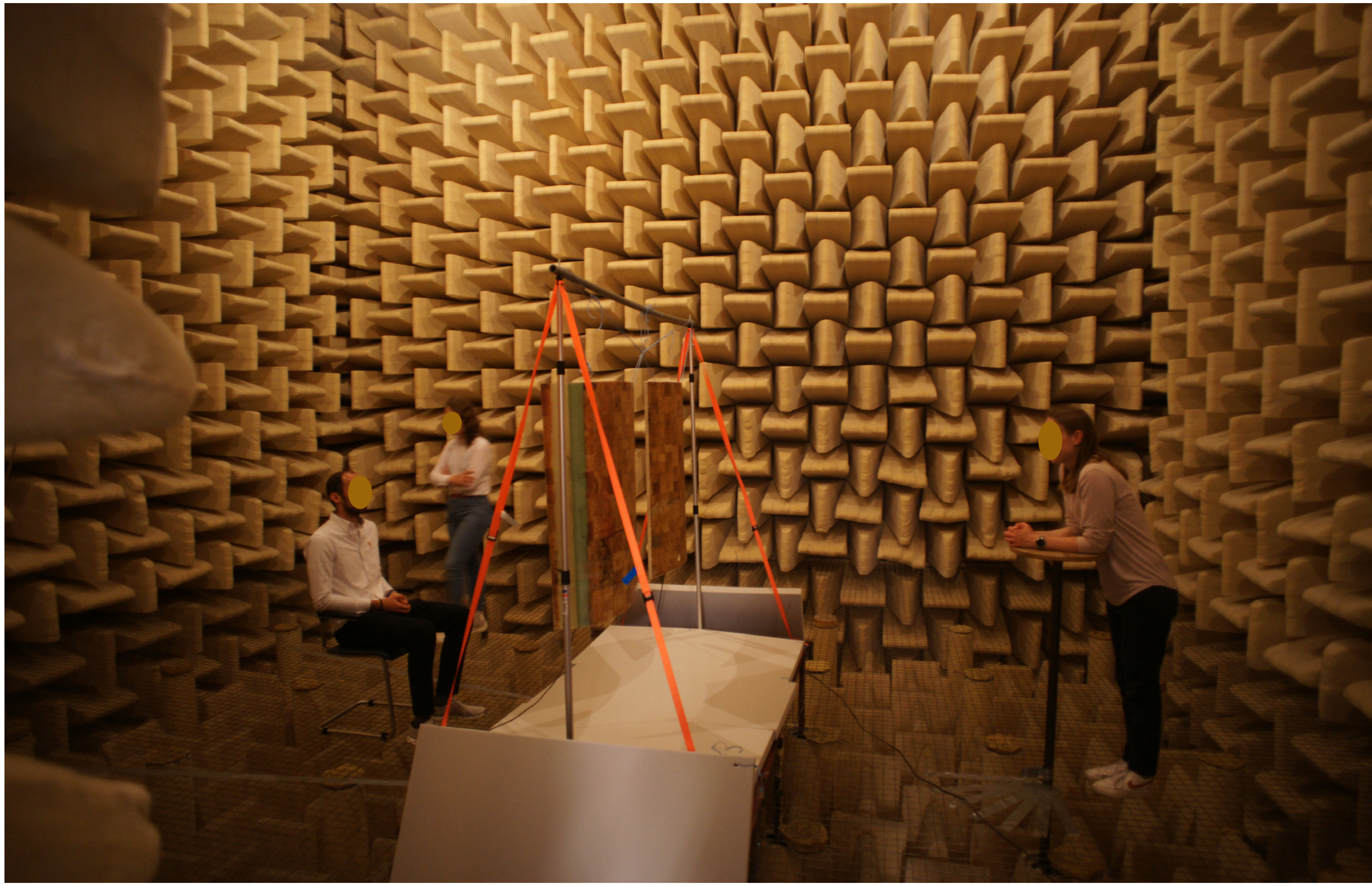


Figure 63: A listening session with listeners moving around the system during music playback.

Figure 64: A secondary listening position facing the backside of the panels.

Discussion (DMLMEX)

The most notable quality of the panels was the amount of low frequency reproduction. Classical knowledge regarding panel speakers dictates that they are well suited at reproducing midrange and some higher range frequencies but lack low-end and upper high-end frequency capabilities. In the qualitative testing, it seemed like the opposite was true for the DWBM panels: they produced surprising amounts of low frequency energy, crisp high frequencies and a somewhat distorted midrange. The amount of low frequency capacity of a panel speaker is largely dependent on its size, where a large panel can produce lower frequencies. The panels in question were quite large, with a dimension of 0,98 m by 0,67 m. The curved nature of the panel could also play a factor, as well as the continuously varying thickness from side to side. In what way these factors affect the capabilities of the panel speaker is unknown. Further research isolating these and other factors could shed further light on their impact on sound reproduction capabilities.

As for the directionality of the system, classical knowledge regarding DML systems often states that they possess excellent sound dispersion characteristics, meaning they radiate a diffuse sound field almost equally in all directions (G. Bank & Harris, 1998). During measurements and qualitative listening experiences, it was clear that this was not the case with the curved panels. When walking around the system during music playback, sharp decreases in volume could be heard when standing at about 45 degrees off-center, which then increased again until it almost completely goes silent when standing at a near 90-degree angle from the surface of the panel. When walking past 90 degrees, toward the rear side of the panels, the sound volume increases again up to its loudest at any point at 180 degrees rotation.

Sitting in between the speakers, facing the back side of the panels (see Figure 64) the sound reproduction was at peak volume and clarity.

Resonance

During the evaluation of the panels in a stereo system, human voices sounded reverberant and nasal. A suspected reason behind this unnatural sounding human voice reproduction might be lingering resonances: the panels are suspended and, therefore, have no way of getting rid of vibrational energy other than its internal dampening and air resistance. A possible reason for this effect only occurring in a limited frequency range could be harmonic resonances in the panel. Wavelengths that correspond with matching dimensions within the panel could be amplified and decay slower. However, to verify this, more experiments are needed. The effect can be studied using a visualization process called waterfall plotting (see Figure 65). Here, the SPL per frequency is plotted over time, showing which frequencies decay quickly and which ones linger. The data processing needed for this operation is outside the scope of this thesis.

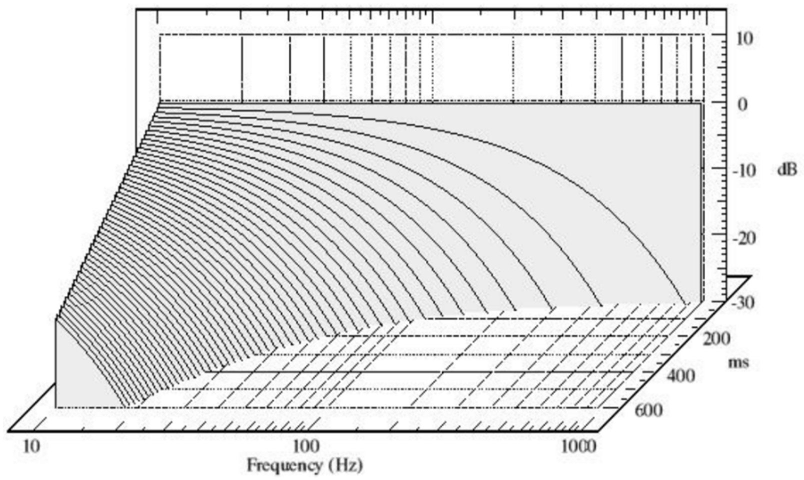


Figure 65: Waterfall plot example where the high frequencies at 1000 Hz decay much quicker than the low frequencies (Fazenda et al., 2006).

Conclusion (DMLMEX)

Based on the qualitative experiences gathered during the DMLMEX testing, it can be concluded that curved WTBM panels have great potential to be used in a musical reproduction application in the form of a DML. Next to this, the curve of the WTBM panel has a direct influence on the directionality of the speaker, where the direction of the curvature influences the overall loudness of the sound when listening at different angles. How the varying material thickness, material composition and panel curvature affect the sound reproduction are all valid areas of further study.

APPLICATION FINDING BASED ON CATSS RESULTS

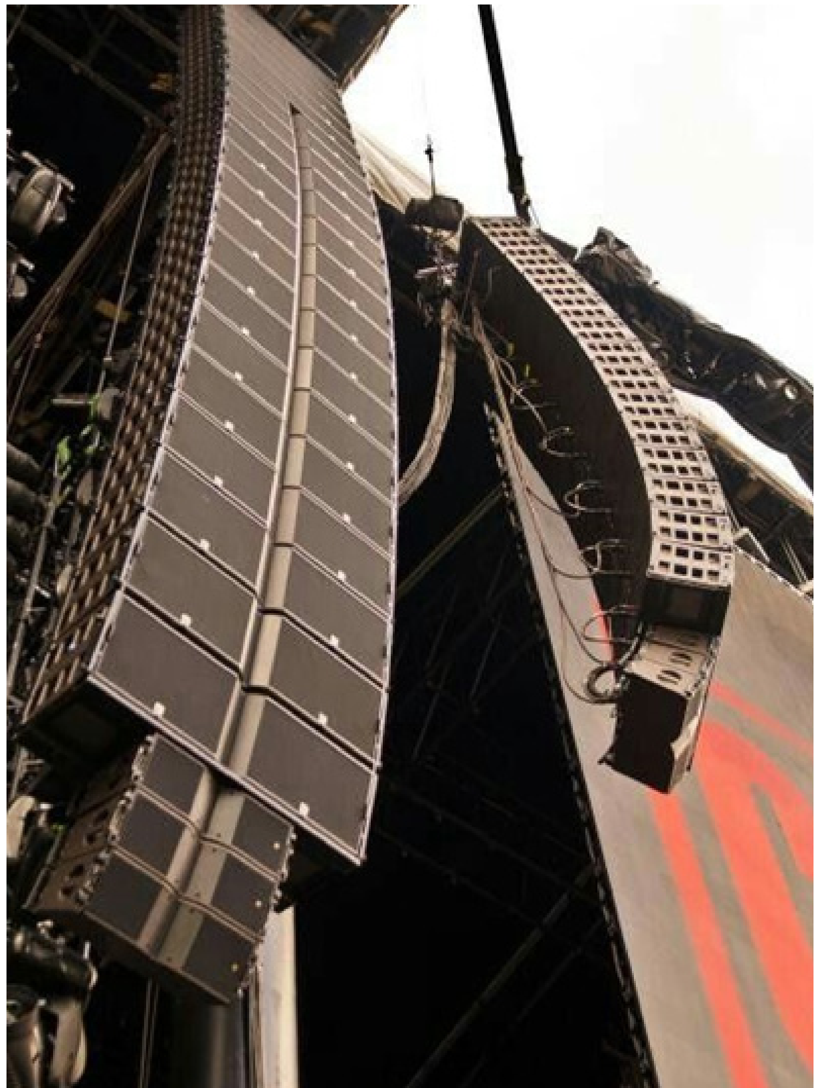
Based on testing data, the following areas of interest were identified regarding the properties of the WTBM:

- TL is adequate compared to panel density.
- TL between 3000 and 5000 Hz strongly fluctuates.
- Music reproduction in the form of a DML is promising.
- Material tends to resonate at very specific frequencies.
- Absorption coefficient is poor.

These areas of interest were used as a source for ideating applications for WTBM. The following section explains which research results the applications were based on, provides a general overview of the application context and outlines the benefits of using WTBM for the application.

Figure 66: Line arrays used on the main stage of Tomorrowland in 2019 (L-Acoustics, Inc., 2024).

Figure 67: A line array system consisting of many modules hung up in the air, weighing more than 800kg.



DML FESTIVAL SPEAKER ARRAY

EXPLOITED MATERIAL CHARACTERISTICS

- Low density.
- Panel shape.
- Musical reproduction as DML.
- Theoretical even sound dispersion.
- Theoretical directional control over sound dispersion.

APPLICATION OVERVIEW

During outside festivals, large groups of people spread out over a large area want to enjoy the performance on stage. To achieve this, massive sets of connected speaker modules are hoisted into the air pointed in multiple directions. These speaker systems, called line arrays, are heavy and expensive and very visible. They must be large enough to produce high amounts of sound pressure across a wide frequency range to service these large festival areas. Figure 66 shows line arrays being used during the Tomorrowland festival in Belgium, where they are in stark contrast against the decoration of the stage.

These line arrays are curved to allow people nearby and far away to experience the same sound. The curvature is achieved by adding many small modules on top of each other with small angles between them, as can be seen in figure 67. They are configured in a vertical stack to better control the directivity of the sound, giving sound engineers at festivals the opportunity to aim the sound where it needs to go, avoiding spillover that can bother the surrounding area. Here, speaker directivity is instrumental to the system performance.

BENEFITS OF USING WTBM

The panels already have curvature, which line arrays need for good sound dispersion. Next to this, current line arrays only curve in one dimension, experimentation with the effect of double curvature on sound reproduction and dispersion could produce interesting results. The sound directivity of each panel can be tuned to give audio engineers high control over where the sound is going.

Additionally, the inherent high stiffness and low density of the material makes it ideal to be hung up on itself, it does not need additional structural reinforcement. It will likely also produce a lighter overall system, since traditional line arrays can weigh a lot; for example, the L-acoustics K2 line array element is considered one of the lightest-in-class but a 16-element array weighs 896 kg (L-Acoustics, Inc., 2024).

The large and mostly flat frontal area of the DML line array can be incorporated into the decor of a festival. They can be painted, or images can be projected on them to make them disappear.

Finally, the high directivity of a curved DML panel can be used next to flat panels that have a more even dispersion, mixing and matching the panels can provide a tailored balance of sound distribution based on the demands of the location.

RESONATING ACOUSTIC AMPLIFIER (RAA)

EXPLOITED MATERIAL CHARACTERISTICS

- Tendency of the material to resonate at certain frequencies.
- Music reproduction as a DML.
- Close material property match to tone woods.

APPLICATION OVERVIEW

La Voix du Luthier is a company that uses resonant materials known from traditional acoustic instrument crafting to make an interesting acoustic object. It is no surprise that their name translates from French into “The voice of the lute maker”. The products they make are examples of a RAA. Here, a volume is constructed using tone wood materials with an exciter strategically placed inside. Figure 68 shows an example of their Onde amplifier, which is a volume shaped as part of a wavefront. The shape and materials of the Onde promote resonances over a wide range of frequencies and together with strategically placed holes it radiates sound in all directions. This way, sound sources can be amplified in a unique way, resembling the method in which acoustic instruments amplify their sound.

Figure 68: The Onde resonating amplifier uses traditional tone wood and internal exciters to amplify music (La Voix de Luthier, 2023).

BENEFITS OF USING WTBM

DWBM should exhibit similar properties to the tone wood featured in the Onde, but it is much more resilient to moisture changes and temperature. Next to this, the double curved shapes present in WTBs provide a basis for more complex resonating volumes, which are much more difficult to produce using wood. Often, flat wooden panels are used for constructing volumes, which is visible in the Pyramide from La Voix du Luthier (as seen in Figure 69).

By incorporating parts of a WTB that are extremely curved and/or have curvature in multiple directions, constructing complex volumes could be possible. Since the resonator requires an enclosed space with many different internal dimensions that correspond to different wavelengths, having complex geometry could prove to be a benefit instead of an obstacle.

Figure 69: A resonating amplifier with a pyramid shaped cavity (La Voix de Luthier, 2023).

SELECTIVE ROOM DIVIDER (SRD) FOR INDUSTRIAL PRINTING ENVIRONMENTS

EXPLOITED MATERIAL CHARACTERISTICS

- Decent TL at specific higher frequencies.
- Low TL at human voice range.
- Low density.
- High stiffness.

APPLICATION OVERVIEW

Many spaces that are used for work can be overly noisy, which can mean sound induced fatigue and injury in workers (Sabato et al., n.d.). For workers in the printing industry, noise is the main health risk on the work floor, with the noise generated from industrial printers peaking at 4000 Hz (Mihailovic et al., 2011). Room divider panels can be used to selectively block off sound from active machinery, leaving room for maintenance and maneuvering around inactive machines. However, since the material has poor absorption, a soft cladding such as PET felt can be used to make an excellent reflection reducing room divider. An example of a room divider can be seen in Figure 70, where the exterior is clad in an absorbent PET felt material (De Vorm, n.d.).

BENEFITS OF USING WTBM

WTBM has the unique ability to selectively block 4000 Hz from travelling through it, but frequencies adjacent or substantially lower to it much less so. This way, active printing machines can be surrounded with room divider panels, lessening the major damaging frequency, while any printing faults, alarms or people calling out from behind the panels can still be heard.

In this scenario, a section of DWBM that is curved can be used as a self-supportive, free standing and relatively lightweight room divider. Here, the specific shape of the divider is not necessarily important, as long as it can stand on itself.

Figure 70: Felt acoustic room dividers often have excellent dampening but poor transmission qualities (AK 3 & AK 4 PET Felt Room Dividers | De Vorm, n.d.).

TRADITIONAL HIFI-SPEAKER SYSTEM

EXPLOITED MATERIAL CHARACTERISTICS

- High stiffness.
- Low density.
- Panel shape.

APPLICATION OVERVIEW

Looking at existing speaker systems, many examples can be found that incorporate composites in their design. The excellent stiffness of composites lends itself well to speaker cabinet construction, since unwanted cabinet movement results in harmonic resonances that can negatively impact the sonic signature of the speaker. When making speaker cabinets, enclosed spaces are constructed with lots of internal struts to increase stiffness, as seen in Figure 71 with Bowers and Wilkin's signature Matrix cabinet construction (801 D4 Signature, n.d.).

Figure 71: The Bowers and Wilkins 801 D4 Signature speaker uses internal reinforcement to decrease enclosure resonance (801 D4 Signature, n.d.).

BENEFITS OF USING WTBM

When selecting a wind turbine blade section to construct a speaker from, care should be taken to pick a shape that requires as little post-processing as possible. A good contender for the speaker cabinet could be the leading edge of the blade as shown in Figure 72. Here, a U-shape is present with internal shear webs.

This shape is high in stiffness, and the shear web provides a flat surface for the drivers to be mounted into. Many speaker designs incorporate a similar shape in their designs, suggesting that this shape is acoustically desirable. An example can be seen in Figure 73, where the shape of the speaker corresponds quite well to the leading edge and shear web volume.

Next to this, using a virgin material with the same high stiffness as WTBM would be very costly for speaker design, as the shape of a speaker is difficult to manufacture. Therefore, using WTBM from decommissioned WTBs can be a low-cost option while getting top-tier performance.

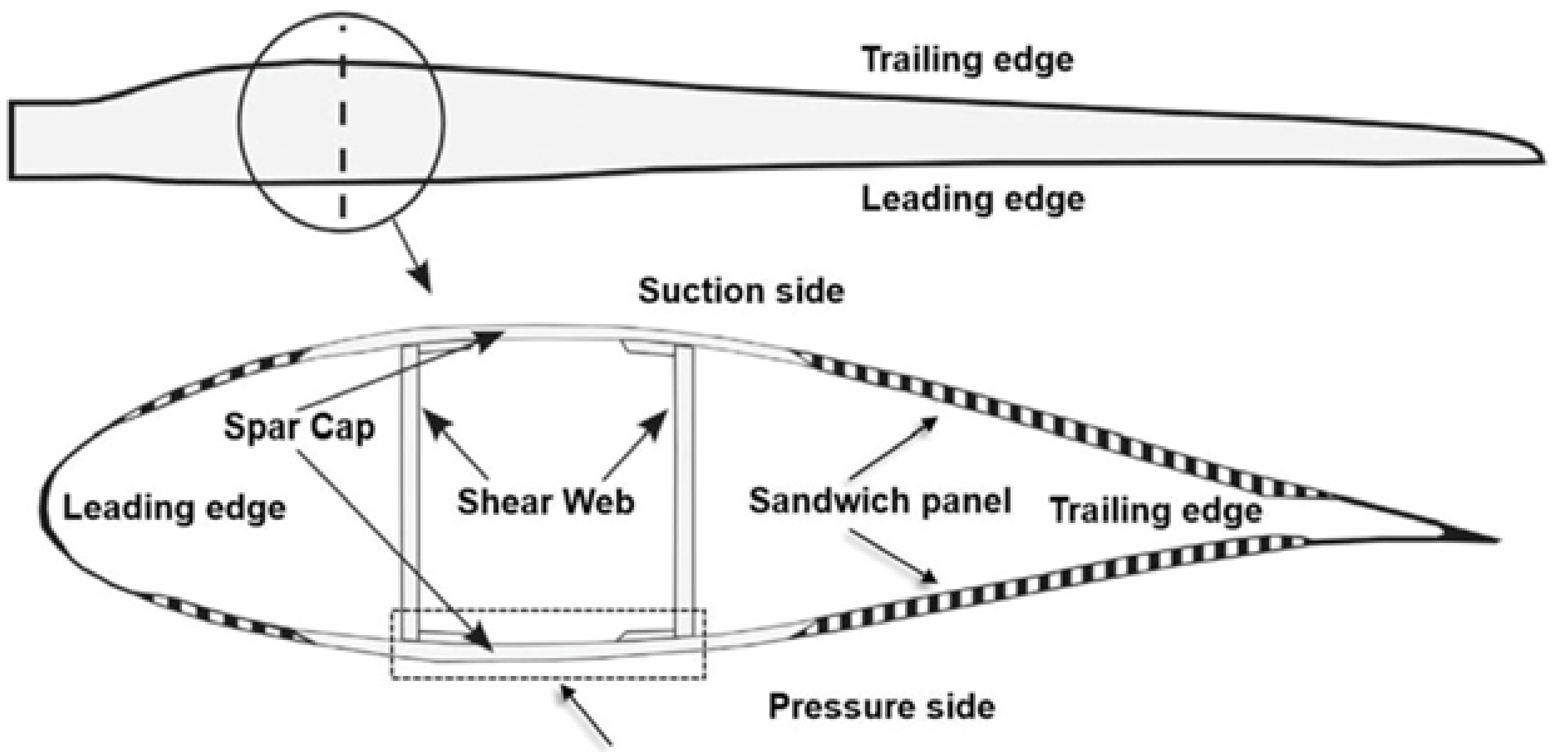


Figure 72: Cross-section of a typical wind turbine blade, where the leading edge and spar cap form an enclosure (Lee, 2021).

Figure 73: The Dali Epicon 6 speaker has a similar curved shape when compared to the leading edge of a wind turbine blade (DALI, n.d.).

ACOUSTIC INSTRUMENT

EXPLOITED MATERIAL CHARACTERISTICS

- Tendency of the material to resonate at certain frequencies.
- Close material property resemblance to tone woods.
- Low density.
- High stiffness.

APPLICATION OVERVIEW

Acoustic instruments such as guitars, cellos, and pianos all use tone boards structures that resonate and amplify the sound they play.

Many musical instruments with a legendary status tend to have been made long ago. String instruments made by the Italian instrument maker Antonio Stradivari are considered among many to be of singular quality. Some studies have been performed on the reason behind these unique qualities, where some conclude that the wood was treated with a mix of chemicals ranging from salt to aluminum (Su et al., 2021). Tonewood with similar properties has yet to be reproduced, making the Stradivari instruments such as the 'Messiah Antonio Stradivari' (see Figure 74) priceless and unique.

It is not impossible to imagine similar conditions for source material in composite instruments. WTBs across the world are constructed using different sandwich structures, thicknesses, filler material and resin. Next to this, wind turbines experience different load cycles, UV exposure and other elemental exposures such as salty, alkaline or acidic water. It would be interesting to study the effects of the conditions during the life of a WTB on its material performance when used in an acoustic instrument. One cannot help but wonder if a cello with a soundboard made from reclaimed composite from Sicilly has a sweeter tone than one harvested from an offshore park in the Bering Sea. However, this falls outside the scope of this thesis.
Simpler instruments, such as a Cajon or a Neck-through

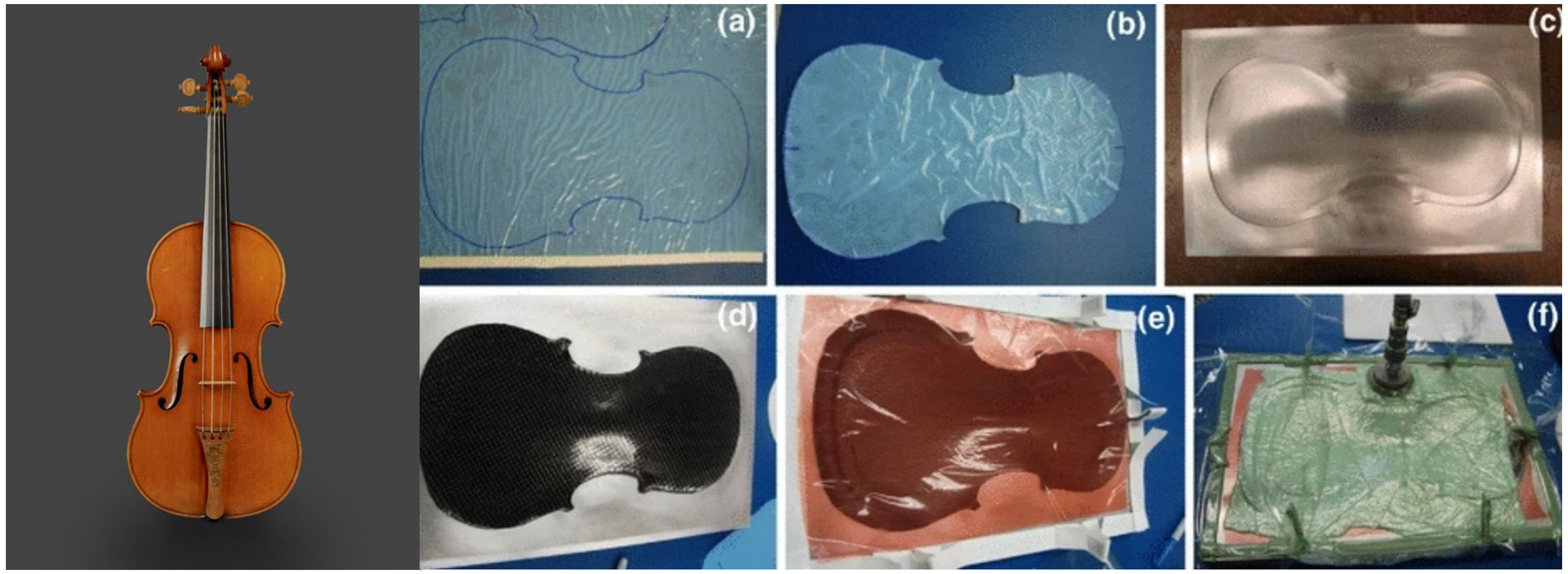


Figure 74: The Messiah Antonio Stradivari violin (left) is estimated to have a value of €20 million (MyLuthier, 2022), will composite violins made today (right) be worth similar figures in 300 years' time (Damodaran et al., 2015)?

electric guitar (see Figure 75) would be more practical to construct.

BENEFITS OF USING WTBM

According to Damodaran et al. (2015) high quality natural tone wood is becoming rare and expensive, while WTBM waste availability is only increasing. Next to this, composites are more resilient to weather conditions, air moisture content and altitude, they remain in key longer. WTBM also has a very high stiffness, making thinner soundboards possible without added bracing to support string tension, resulting in lighter instruments.

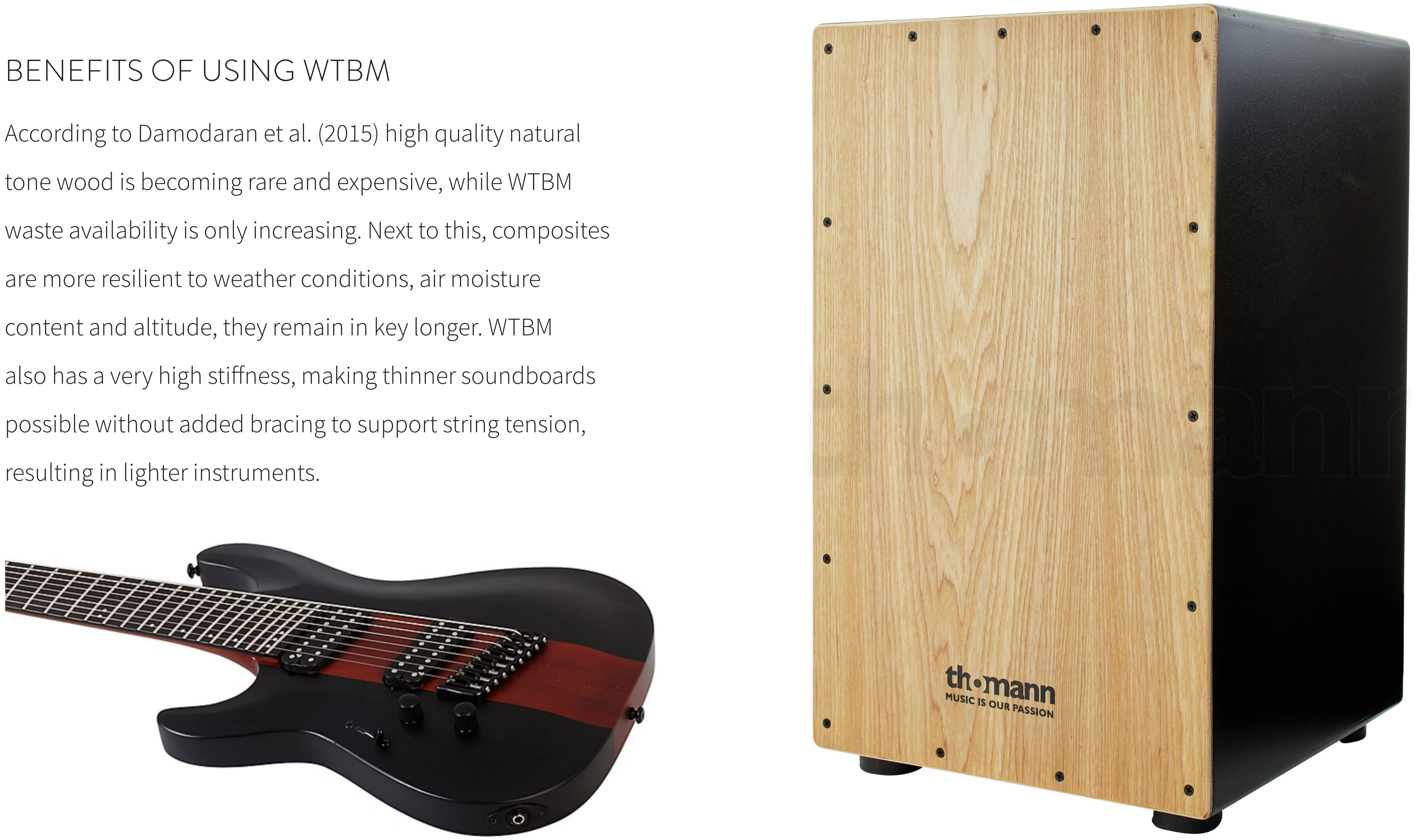


Figure 75: A solid body guitar (left) made from two different varieties of wood (Schecter Guitar Research, n.d.) and a Cajon (right) made from wooden panels (Thomann, n.d.).

EVALUATING APPLICATIONS

To find applications that are most suited for both the material and this MSc project, evaluation parameters need to be established. The categories of evaluation are based on the list of goals and nice-to-haves defined in the chapter Research goal. The concept will be valued highly if it:

1. is based on at least one specific material property that WTBM excels at (but more is better).
2. (potentially) performs as well as or better than the material currently used in the application.
3. is feasible (within the project scope).
4. is feasible (can be realized in the real world).
5. is viable.
6. is desirable.
7. showcases a novel way of using WTBM.
8. replaces a (virgin) material with high embodied energy costs.
9. requires little reprocessing of the original material.
10. has a “wow-factor” that helps call attention to the WTBM waste problem.

1. Research synergy: How much overlap is there between the application and the knowledge gained during the research phase of this thesis?

2. Outperforming application: How well does WTBM potentially perform in the application when compared to the currently used materials?

3. Project feasibility: can the application be prototyped within the confines of this graduation project?

4. Real world feasibility: Can the application be realized using current manufacturing techniques?

5. Survivability: Will the product remain standing in the market?

6. Desirability: Is there a market for the product? Do people want to have it?

7. Novelty: Does the application showcase a novel way of using WTBM?

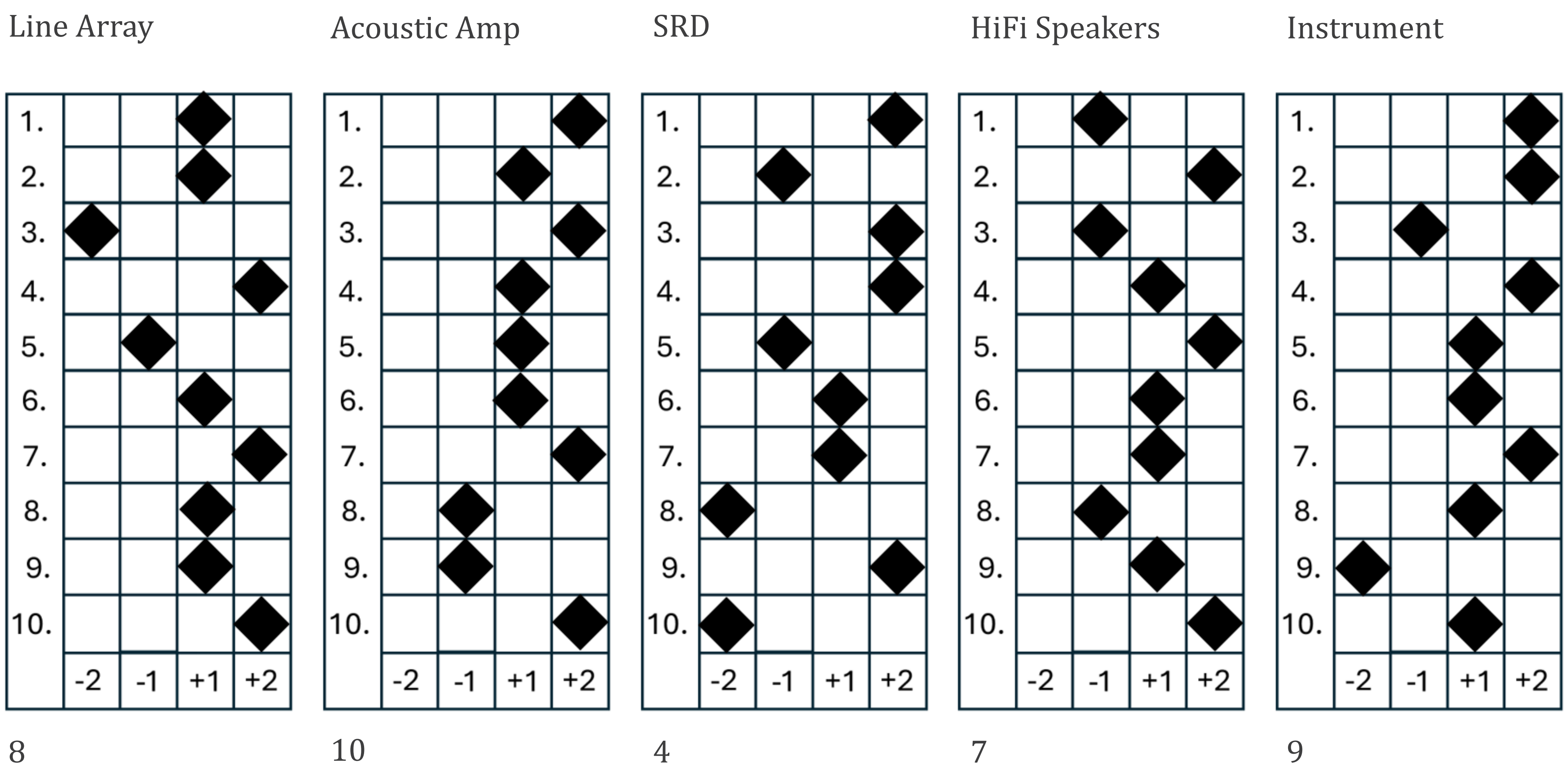
8. Impact: What is the (positive) impact when substituting DWBM for the currently used material? This can be environmental, make the object more effective in its application, make the world a better place.

9. Low embodiment effort: How little does the source material need to be altered to fit the application? Does the application call for added materials, lengthy manufacturing or high amounts of manual labor?

10. Awareness potential/wow factor: What is the potential for the concept to catch the public eye, to capture the imagination of people in places with the power to make meaningful decisions? Since the issue of wind turbine blade material waste flow is an emerging one, projects that spread and increase public awareness are of value.

HARRIS PROFILES

Using a Harris profile, the applications are each evaluated on the parameters defined in the previous section and are given a score between -2, -1, +1 and +2 (where -2 means it fulfills the validation parameter very poorly and +2 means it fulfills the validation parameter very well) as seen below.



FINAL PICK

Based on the scores, both the line array, acoustic instrument and acoustic amplifier are solid concept directions. However, the line array has the lowest score for project feasibility and is, therefore, not an optimal choice for embodiment within this project. The acoustic amplifier and acoustic instrument concept ideas are very close, with the acoustic amplifier having the overall highest score. Additionally, since the acoustic amplifier scores higher in the first seven parameters, which were based on goals, and scores high on wow factor it is the best choice for embodiment.

Therefore, the acoustic amplifier concept will be chosen to embody for a showcase during the end presentation of this thesis.

FEASIBILITY

Project feasibility

The raw materials for constructing the prototype are already present in the form of WTBM panels previously used in the TL and DML acoustic testing phase, so there is no need for material acquisition. The size of the RAA is moderate, so handling, transporting and shaping will not be a big challenge. Designing the shape and features to make the acoustic amplification work as intended requires some iterations and additional research, but it is anticipated that this will not be a major hurdle. Before physical prototyping, some mock-ups can be made using lo-fi rapid prototyping methods, and a CAD model can be made to accurately size components up before committing them to cutting processes.

Real world feasibility

Large scale processing techniques for repurposing WTBM are starting to emerge but are not mature yet, so initially only small scale production with a high degree of manual work will be possible. Cutting methods for medium to small sized panels are known and reasonably accurate, the most notable being CNC waterjet cutting. The costs of WTBM are not well documented but as a waste stream it stands to reason that the raw materials do not need to be expensive. Considering these factors, the acoustic amplifier seems feasible in the real world context.

Desirability

Since the company that pioneered the RAA concept using tone wood got the concept off the ground, it has gained some attention. Most notably, legendary film score composer Hans Zimmer has used an acoustic amplifier from La Voix de Luthier in his soundtrack for the recent hit film Dune. Interest is especially present amongst synthesizer enthusiasts and experimental musicians. If the jump can be made to a more general public remains to be seen, but there has been a small but dedicated market for it up until now. The added effect of using recycled materials in the speaker might appeal to a somewhat younger audience.

Next to this, according to Greenpeace (2010), high quality natural tone woods are becoming scarce and more expensive. This means that finding a suitable and sustainable alternative to natural tone woods will provide significant benefits to manufacturers that use tone woods.

Viability

The long-term survivability of the concept is difficult to predict. The current clientele of the La Voix du Luthier products is willing to buy the current products at moderately high prices, ranging from € 690,00 to € 2459,00. The demand seems to be higher than the supply since many of the product in the online store are not in stock as of writing this thesis. Part of the reason for this is that each product is completely built by hand by a skilled craftsman, making the manufacturing slow. To ensure the survivability of the product, manufacturing lines with more efficient processes will help raise up the production rate without sacrificing much on the craftsmanship and quality.

Ensuring a steady supply of raw materials will not likely present itself as an issue, since the WTBM waste stream is only projected to grow in the coming decades. Setting up a process to find the highest quality materials, pre-processing them and transporting them to the manufacturing location will be the biggest challenge, and it will require a network. However, the network does not have to stretch out too far, since wind turbines are predominantly placed along the coast, making western Europe a hotspot for wind turbines and, thus, wind turbine waste. It remains a niche product, so scaling will be challenging unless a larger market can be secured.

CONCEPTUALIZATION

To evaluate the suitability of WTBM in the acoustic application of a tone board made from classical tone woods such as Sitka Spruce, a concept was developed for a RAA made from available WTBM panels. The conceptualization followed a classic design loop with visualization, embodiment, validation and evaluation. Normally, this would be an iterative process where the results of the evaluation phase would be used as the start of a new ideation loop. However, due to the limited time, only a single loop was executed to produce a proof-of-concept prototype with a technology readiness level between 3 and 4. Qualitative testing in a semi-controlled environment was conducted to formulate a preliminary conclusion on the feasibility of the concept.

ORIGINAL CONCEPT OVERVIEW

Since the concept was inspired by an existing application, this original application must be reviewed to extract valuable information regarding its form, function and principle.

The RAA is certainly nothing new, since it is the same basic function that the resonating bodies in acoustic instruments have been fulfilling for hundreds of years. The difference between something like the Voile from La Voix du Luthier (see Figure 76) and the resonating body of a modern acoustic guitar is the way in which the sound energy is introduced to the resonating body. With acoustic (string) instruments, the vibration of a tensioned string is transferred to the surface of the resonator through a solid connection. With the resonating acoustic amplifier, a transducer (also known as an exciter) is bonded directly to the surface of the resonator and vibrates according to an amplified electrical signal that it receives. This way, any electronic instrument, like a synthesizer, can be hooked up and played to sound like an acoustic instrument.

In the Voile, the resonating panels are freely suspended using leather strips, which means that they experience very little damping and can resonate more freely. The back side resonating panel is curved or 'sail-shaped' enhancing the tone it produces, according to the manufacturer.

Figure 76: The resonating acoustic amplifier La Voile from La Voix du Luthier with suspended vibrating panels, including a curved 'sail-shaped' panel on the back (La Voix du Luthier, 2023).

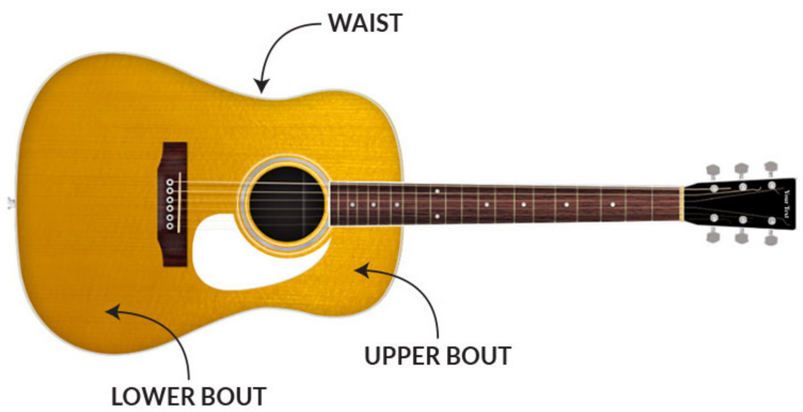


Figure 77: The parts of a typical acoustic guitar body (Banner, 2023).

In the case of an acoustic guitar, the shape of the resonating body is both acoustically and ergonomically functional. The waist, shown in Figure 77, makes resting the guitar on a leg more comfortable while sitting but also influences the tone generated by exciting the guitar strings. According to Banner (2023), the curvature size, size ratio between the upper and lower bout, waist width and the opening underneath the strings all influence the tone of the guitar.

This principle can be seen in another resonating acoustic amplifier from La Voix du Luthier, the Onde (see Figure 78). The two largest opposed surfaces have an exciter bonded to them internally, which enhances the loudness and clarity of the sound produced by the Onde.

This shape is similar to a section of a guitar body, when divided equally along is longest axis and removing the curved ends (see Figure 79) or the body of a grand piano (see Figure 80).

Figure 78: The Onde amplifier showing the distinct openings and curvatures of the design (La Voix du Luthier, 2023).

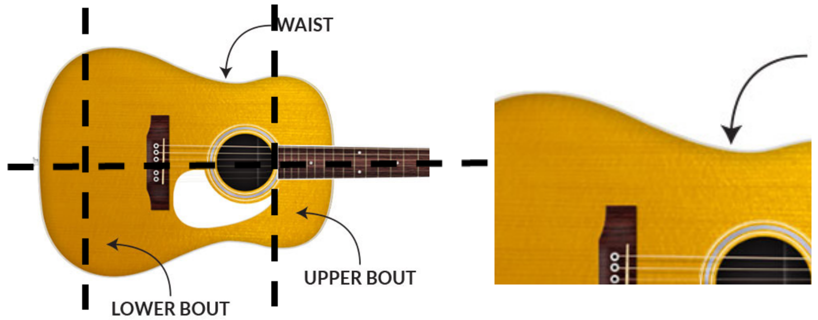


Figure 79: A section of a guitar representing the rough shape of the Onde.

Figure 80: The Onde has a similar body shape compared to a Steinway & Sons Model L grand piano (1994 Steinway Model L Grand Piano, n.d.).

In the Onde, the continuously varying shape of the body encourages resonances across different wavelengths and the variously sized holes ensure an even dispersion of sound in all directions. The continuous variation in shape along with varying hole size is also present in the biggest product from La Voix du Luthier, the Pyramide (see Figure 81).

Here, it can be seen that the Pyramide RAA is much larger than the Voile RAA. The internal volume of an acoustic resonator has a pronounced effect on its sound characteristics. The manufacturer of these resonating acoustic amplifiers characterizes the sound output of the three models according to the overview seen in Figure 82.

Figure 81: The Pyramide RAA next to the Voile RAA from La Voix du Luthier, with a striking pattern of differently sized sound holes across the back and larger triangular holes in the front (La Voix du Luthier, 2023).

This shows that a simple closed volume does not suffice for a resonating acoustic amplifier, its shape, size and openings need careful consideration. With this in mind, the concept ideation could be carried out with some basic principles established:

- Larger internal volumes make more bass.
- Freely suspended resonator panels produce more precise sound, but less bass.
- Curved panels can enhance sound output.
- Smaller internal volumes produce better transients.
- Enclosed volumes with openings of various sizes are essential for sound projection.
- Exciters need to be placed on opposing panels for better volume.

Figure 82: Ratings per sound characteristic across the three models in the lineup of La Voix du Luthier (La Voix du Luthier, 2023).

CONCEPT IDEATION

Since the time frame for conceptualization was limited, material sourcing was not viable. Therefore, an overview of the currently available materials at the Faculty of Industrial Design Engineering (IDE), Delft University of technology was made (see Figure 83).

The following goals for the concept were formulated beforehand:

- Include a sail shaped panel.
- Use opposed actuated sound boards.
- Showcase the WTBM composite panel structure.
- Incorporate the origin of the material in the design.
- Have an even distribution of sound in all directions.
- Use only reusable fasteners.

Using the available panels and the formulated goals, various configurations were generated during a brainstorm sketching session (see Figure 84).

Figure 83: Overview of the available composite panels at the IDE faculty.

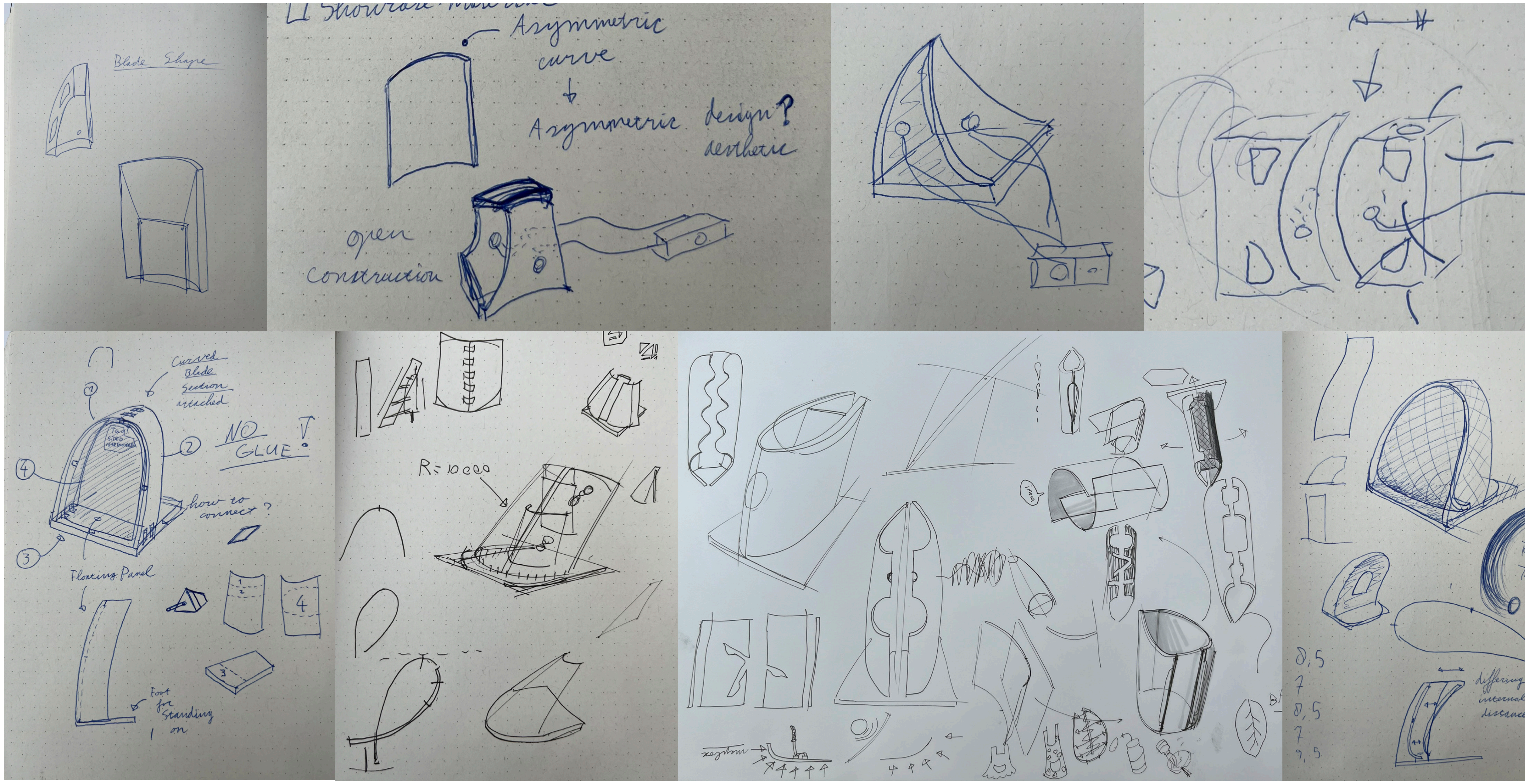


Figure 84: Examples of sketches generated during a brainstorm drawing session.

Various configurations were quickly reviewed by temporarily fastening panels together to form shapes (see Figure 85).

Figure 85: Quick and dirty shape exploration of generated concepts using available WTB panels.

Based on generated sketches and shape explorations, a promising configuration was found (see Figure 86).

Here, the curved panels oppose each other to create a large continuously varying internal volume which promotes loudness, bass response and a wide spread of resonating wavelengths. Inside the cavity, a smaller thin panel can be freely suspended to produce higher frequencies. The curved panels have been used during earlier testing in the form of DML panels, in the anechoic environment. Therefore, the panels were already fitted with exciters. Next to this, the sound dispersion of a single panel was very directional, with the strongly curved sections producing very little sound normal to its surface. By placing the panels in this opposed configuration, the sound output of the curved sections should sum and produce a louder sound, while the flatter sections of the panel radiate outward. Combined with the internal free-hanging panel aimed towards the opening

Figure 86: A promising panel configuration with an internal free-hanging panel surrounded by opposed curved panels.

between the curved sections, the overall sound dispersion can be tuned to be very even all around the resonator. Figure 87 shows a concept sketch, with a preliminary name: the WingTone.

Intentionally, the opposed curved panels resemble the aerodynamic shape of a WTB, highlighting the origin of the material. The unfinished surface combined with large openings that show the inside also showcases the composite material.

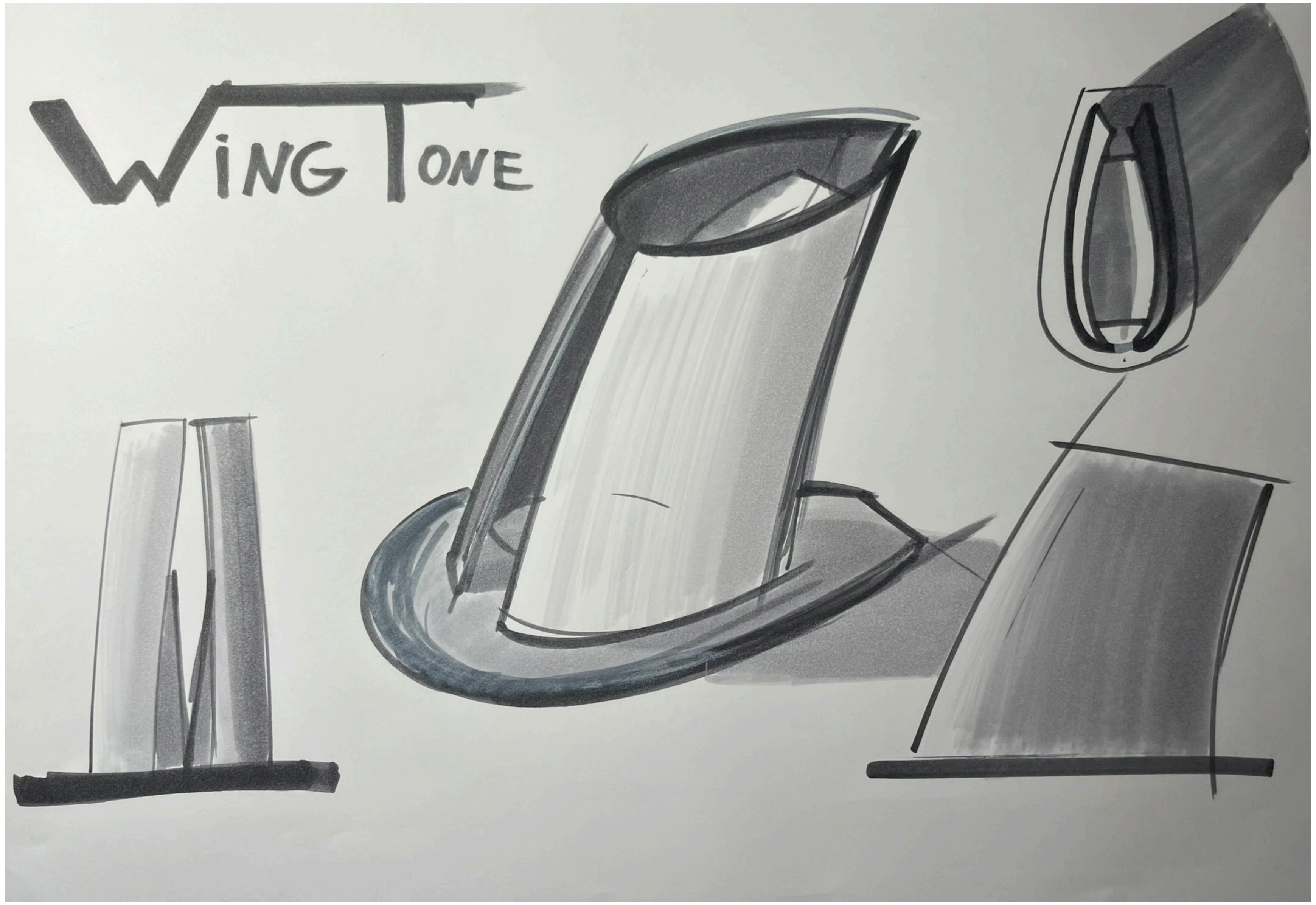


Figure 87: Concept sketch of the WingTone, a resonating acoustic amplifier made from reclaimed WTBM.

CONCEPT EMBODIMENT

From the visualization sketch and the available panel dimensions gathered earlier, a CAD model was constructed in Solidworks which can be seen in Figure 88.

Here, the front gap was widened to allow the internal panel to project more sound towards the front.

Figure 88: Renders of a CAD model made from available blade sections.

From the Solidworks model, dimensions for each panel were derived. The panels were then cut to size using a reciprocating saw, ensuring that proper personal protection was used. The panels were fastened using metal L-brackets and M4 bolts as shown in Figure 89.

After constructing the main volume, the smaller panel was installed using thin rope and M4 bolts, with large washers added to securely clamp onto the rope (see Figure 90).

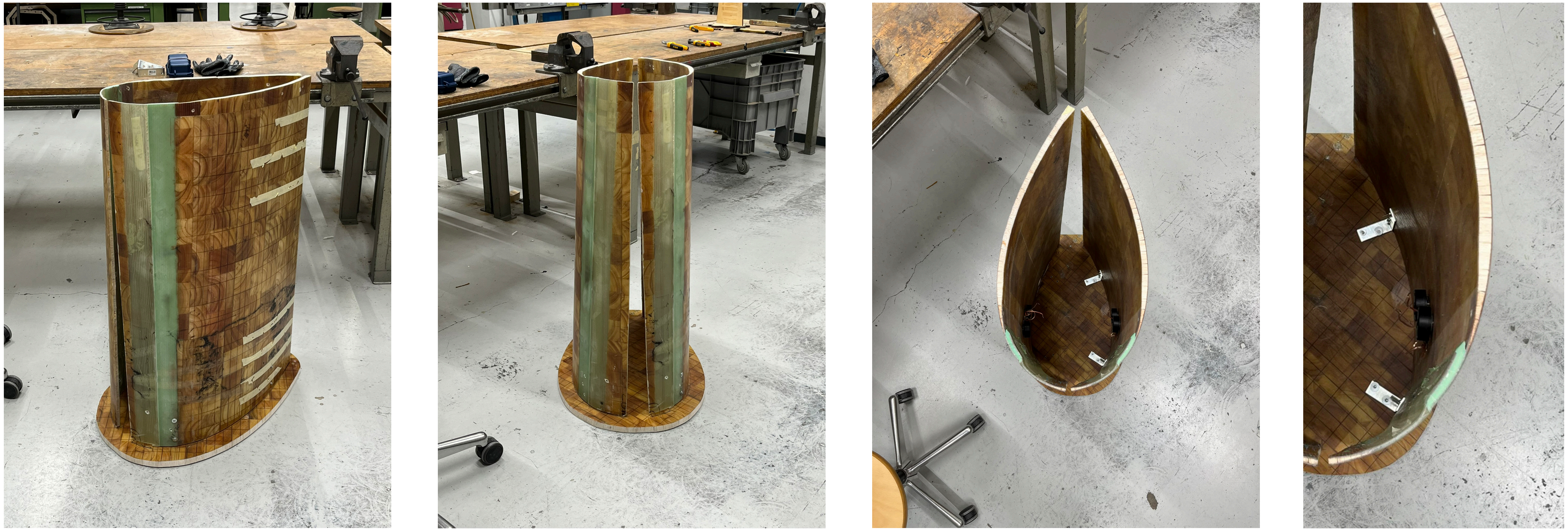


Figure 89: The main volume of the WingTone was made by bolting the curved panels to a bottom plate with L-brackets (see image on the far right).

Initially, the smaller free-hanging panel was also supposed to be fitted with an exciter. However, due to the added complexity of this design, where an additional amplifier was needed to drive it, it was decided to first test the prototype without it. The panel should still play a role in deflecting internal sound towards the front and back of the resonator, adding to the even dispersion of sound. Additionally, the front sound hole was not widened, since it was unfeasible to cut using the reciprocating saw. Next to this, the amount and the size of the openings in the prototype were already quite large, ranging from 5 cm to 2 cm in the front. The back opening ranges from 8 cm to 3 cm. Thus, a widening of the frontal gap was deemed to be unnecessary.

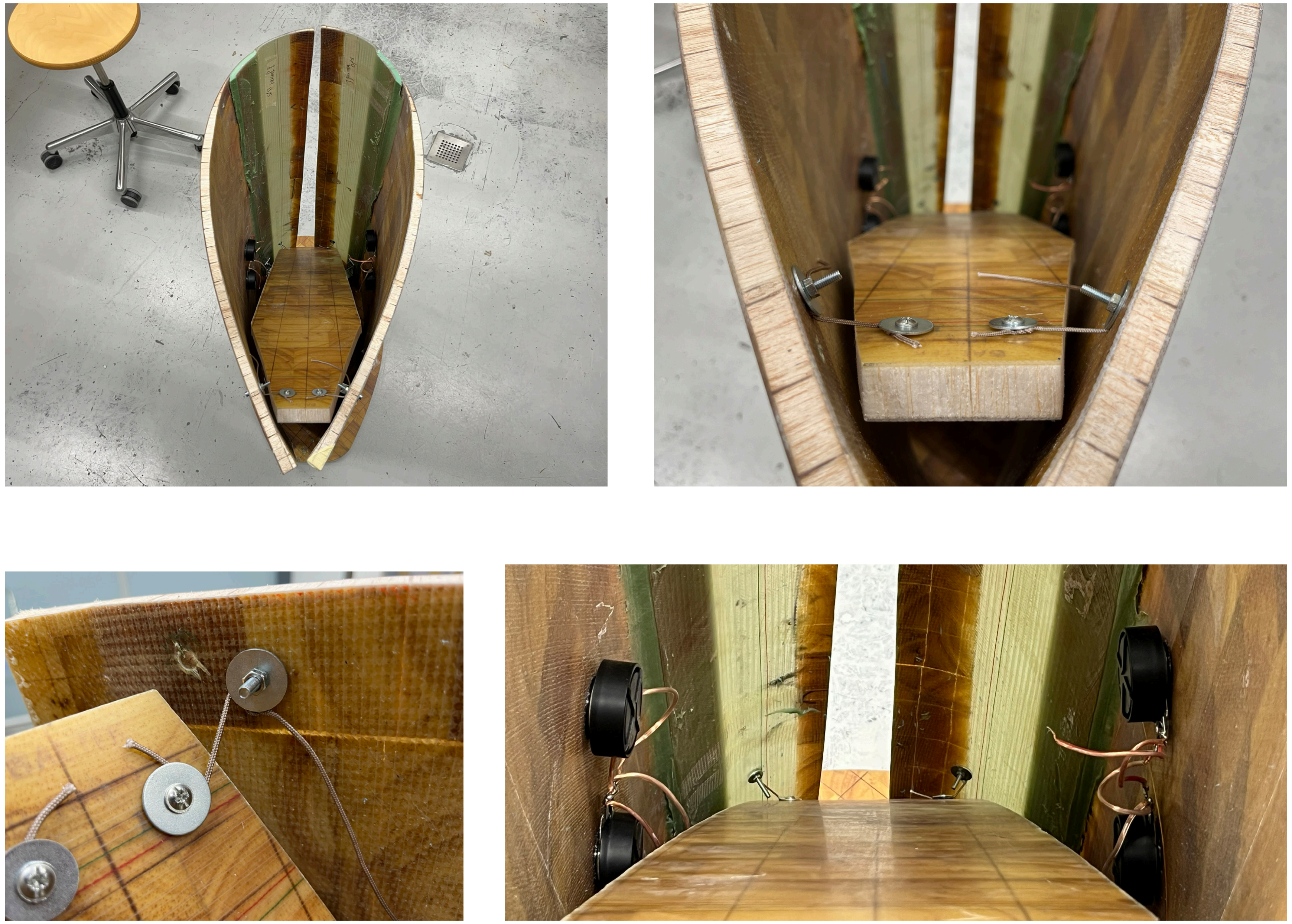


Figure 90: The smaller internal panel of WingTone was suspended using thin rope on four corners, letting the panel hang freely between the curved panels.

PROTOTYPE VALIDATION

The goal of this prototype was to find out whether WTBM is a suitable replacement for natural tone wood. To evaluate this, a RAA constructed out of WTBM was used in a small qualitative user test. The participants were recruited by means of convenience sampling. No inclusion criteria were used. In total, 9 participants took part in this study.

VALIDATION METHOD

Since a RAA is meant to amplify digital sound signals in such a way that they sound like an acoustic instrument, the test consisted of playing digital files of a singular guitar. The dispersion of a RAA should be as omnidirectional as possible, since actual acoustic instruments also radiate sound omnidirectionally. Participants were asked to evaluate both the authenticity of the sound and how even the dispersion of sound into the room was. For that, they were asked to give their opinion on:

1. How close to an authentic acoustic instrument does the RAA sound?
2. How omnidirectional is the sound produced by the RAA?

Before the tests, two hypotheses were made:

1. The RAA sounds very close to an authentic acoustic instrument.
2. The sound generated by the RAA is perceived as very similar in tone and loudness. regardless of the off-axis position of the listener.

The test setup (see Figure 91) consisted of the RAA prototype that was set up in the middle of a large room with four listening positions (A, B, C and D indicated by 4 chairs positioned around the RAA prototype).

Each participant was first asked to sit in chair A and acoustical guitar music was played through the RAA for approximately 90 seconds. After that, the participant was asked how realistic the sound was on a scale of 1 to 5, with 1 being not realistic at all and 5 being indistinguishable from a person playing the guitar in the room. Next, the participant was asked to move around the room from chair A to B to C and then D during the next song. The participant could choose when to move but was asked to try and sit on each chair for around 60 seconds. If participants lingered too long, the researcher encouraged them to move to other listening positions. During this part of the test, an acoustic guitar fragment differing from the fragment that was played during the initial 90 second test was played through the RAA. After the participant sat in every chair for at least 60 seconds, the acoustic guitar fragment was stopped and the participant was asked the question: What is, if any, the difference in sound between each listening position? Finally, the participant was asked if they had any additional remarks.

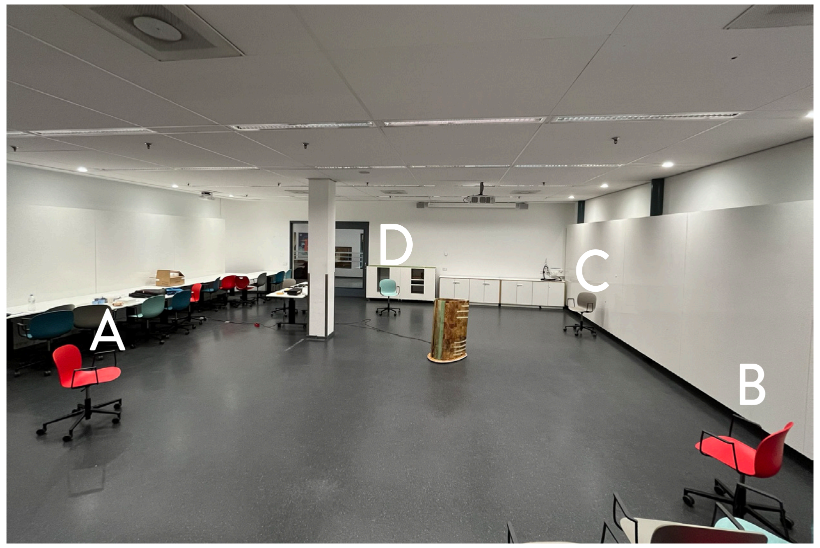


Figure 91: User test setup with the RAA in the middle of the room and four listening positions (A, B, C, and D) around it.

VALIDATION RESULTS

Since the sample size of this study is too small for drawing statistically significant quantitative conclusions, the question results serve as a qualitative indication of the overall experience of the current prototype. The scoring system for question one was provided to give the participants something to base their answers on, instead of having to describe the sound experience with words. Since the prototype aims to validate something relatively intangible, asking participants to score something on a scale aims to make it more tangible. After this, participants were asked to provide a reasoning behind the specific score, providing rich qualitative data. The scoring results can be seen in Table 5.

The average realism score was 3,8 out of 5, leaning towards "quite realistic". Relevant general remarks provided by the participants included:

- "Has a real resonating sound quality to it, similar to a real guitar."
- "It is not very pleasant, really only guitar sounds and nothing else."
- "It sounds very acoustic, made me realize how little purely acoustic music I listen to."
- "Very interesting, it does not look like a speaker but sounds impressive."
- "I am so used to bass heavy music that I am really missing it here, but I guess it is not supposed to be present in this type of music."
- "I am impressed by the simple design; it plays quite loud and fills this big room."
- "I can almost see the guitarist playing in the room, very realistic."
- "It sounds 'hollow', as if the guitar is being played in a large room."

Table 5: Scores per question given by each participant.

	P1	P2	P3	P4	P5	P6	P7	P8	P9
Q1 Authenticity	4	5	4	4	3	2	3	5	4
Q2 Sound difference	Not much	Not much	Not much	Not much	Position B more volume	Almost none	Some differences	Not much	Position B sounds a bit louder

PROTOTYPING CONCLUSION

Based on the qualitative testing, the perceived realism of the RAA prototype was quite high. Next to this, the perceived omnidirectional sound dispersion of the RAA in the room was quite high as well. Together, these two parameters indicate that WTBM can be used to produce an RAA that sounds authentic and omnidirectional, making WTBM similar in its acoustic properties compared to natural tone wood.

DISCUSSION

At the start of this study, the following research questions were raised:

1. What are the material properties of end-of-life WTBM?
2. What are suitable applications for repurposing end-of-life WTBM?

To answer these questions within the timeframe of this thesis, the research area was rescoped to acoustic material properties. Literature research allowed the identification of a knowledge gap regarding acoustic material data, which was partly responsible for the rescoping of the project. Experiments were conducted to gather relevant acoustic material property data of WTBM in the form of damping, TL and performance as a distributed mode loudspeaker. The tested material possessed low damping, decent but highly fluctuating TL across a wide frequency range and promising performance as a DML. Using these results, along with additional material data synthesized in Ansys Granta Edupack, performance indices were formulated to compare the acoustic performance of WTBM sandwich panels to known materials. Materials with similar acoustic properties to WTBM sandwich panel were identified, reviewed and relevant acoustic applications linked to these identified materials were uncovered.

Five of the identified acoustic applications showed a high potential to be feasible, viable and desirable. The three most relevant applications that were identified were a DML line array system, a RAA and acoustic instruments. These three applications all stem from the similarity of WTBM to natural tone wood, most notably Sitka Spruce. High grade natural tone wood availability has significantly decreased, which means that WTBM could have a real and lasting impact on the tone wood industry as a potentially more sustainable substitute.

The RAA was chosen as the most feasible of the two applications for prototyping, as well as the most impactful in terms of its showcase potential.

A prototype was constructed that aimed to meet the goals and nice-to-haves stated in the introduction, where it:

1. Was based on at least one specific material property that WTBM excels at.
   The prototype was based on the excellent theoretical overlap between the mechanical/acoustic material behavior of tone wood and WTBM sandwich panels, stemming from its flexural modulus to density ratio.

2. Performed as well as or better than the current form of the application.
   The first iteration of the prototype was not studied enough to judge its objective performance, but initial perceived performance indicated a high degree of authenticity.

3. Was feasible, viable and desirable enough to justify its existence.
   The prototype was not complex to build, tapped into a growing waste material stream as its main resource and had a niche but existing market.

4. Had an acoustic function.
   The prototype's main function was acoustic, where it amplifies electronic signals in a natural and acoustic manner.

5. Showcase a novel way of using WTBM.
   As of writing this, no other examples of using WTBM for this function were identified.

6. Replaced a virgin material with high embodied energy costs.
   The replaced materials, Sitka Spruce and other tone woods, were virgin materials. The embodied energy of this material was not studied, but the material is critically low in availability due to insufficient regrowth and high demand.

7. Required little reprocessing of the original material.
   The prototype used WTBM in its raw form, limited reprocessing in the form of reshaping and drilling holes was required. If desired, re-finishing was optional but not necessary for the acoustic performance.

8. Had a "wow-factor" that helps call attention to the WTBM waste problem.
   The prototype employs a novel form of producing sound from an unrecognizable shape, which was perceived as surprising. How much attention the prototype called to the growing WTBM waste problem was not studied. However, since the aesthetic prototype design showcases the raw material and references the origin of the material through its form, it had a high potential for being used as a showcase for highlighting WTBM waste issues.

User testing with the RAA prototype indicated that WTBM has the potential to be used in applications where tone wood is used, since the authenticity of the acoustic sound and the omnidirectional dispersion were perceived as high.

LIMITATIONS

The TL material data gathering was done using adapted standards, meaning that obtained results could not directly be compared to existing material data found in the literature. This was partly remedied by including a calibration material. However, more research is necessary to draw strong conclusions on TL of WTBM.

The panel size that was used for testing was smaller than desired, limiting the frequency range across which the data was accurate. Next to this, there are more relevant acoustic material properties besides TL that can be measured with more technically advanced measuring techniques which were unavailable during this research. Furthermore, identifying a performance index for comparing materials based on acoustic performance is a complex and scarcely documented process. The performance indices were constructed based on solid foundation of theoretical knowledge but remain partly unsubstantiated regarding their direct impact on actual acoustic material performance in various applications. The speed of sound in a material and panel bending stiffness of a material is indicative of certain acoustic properties, as is its density, but they are not the only ones. To gain more control over predicting material acoustics, more research on the specific impact of individual performance indices on acoustic behavior is needed.

The RAA was deemed to be the most relevant application to prototype for showing the potential of WTBM in the role of tone wood materials. However, since RAAs are a relatively new and scarcely documented phenomenon, it makes it difficult to know if the prototype is similar to the actual product. Next to this, sound and especially music are abstract and subjective phenomena, making them difficult to be empirically tested. Altogether, this made the results of the prototyping and user testing merely an indication towards the potential of WTBM as a replacement of tone woods and not a proof of concept.

Finally, the last prototype construction and validation study were conducted within a limited timeframe and a limited number of participants. This resulted in general indications and trends of what participants perceived rather than any definitive proof of concept. Next to this, the RAA is meant to be used with an electronic instrument as its source after which it produces the received sound in an acoustic manner. Since this research did not have access to a musician or music files with pure sound input data, regular recorded music was used. This is not the best way of showcasing the RAA prototype. Acoustic music is produced by an instrument vibrating the air in a room, which is recorded and sent to the RAA which acoustically transmits this sound into the air of the testing room. This meant that the original music was effectively played by an acoustic instrument twice, which undoubtedly had an impact on its perceived authenticity.

FURTHER RESEARCH

Further research regarding the acoustic properties of WTBM should include collecting more accurate TL data using the two-room method and accurate damping data using the reverberation room method. Next to this, robust methods for measuring internal damping, acoustic converting efficiency, radiation ratio and characteristic impedance of WTBM should be explored.

The relevant acoustic applications identified by this thesis warrant additional research in the form of prototyping and (user) evaluation. The acoustic performance of WTBM could be further examined by exploring its performance when used in a traditional acoustic instrument. By (partly) constructing an acoustic instrument from WTBM and directly comparing its performance to a similar instrument that uses natural tone wood, a more objective evaluation could be performed. HiFi speakers have a large market, and examples of speakers made from high-performance composites are already known. Next to this, making DML line arrays for festival music systems has potential benefits over existing solutions and at least one example of composite DML line arrays exists, showing that pursuing this application has merits.

The acoustic performance of WTBM used in a RAA should be investigated more in-depth. Measuring objective performance in the form of frequency response, resonance decay and sound dispersion could be directly compared to an existing RAA made from natural tone wood. Next to this, subjective testing could be done with a larger body of participants to assure high confidence level of obtained results. Also, the sound source for subjective testing using the RAA should consist of direct output from an (electronic) instrument, not a recorded piece of music. The first design iteration of the RAA made from WTBM should be used as a basis for additional iterative design sessions to improve its performance.

Finally, a study on the environmental impact of substituting WTBM with natural tone wood should be performed to showcase how sustainable such a substitution could be.

CONCLUSION

The research question of finding material properties was successfully answered. Information regarding damping and TL was generated, as well as objective and subjective data on the acoustic performance in the role of a DML. The research goal of finding suitable applications for end-of-life WTBM was achieved. Within the framing of acoustic material behavior, several relevant applications were found. Of these applications, the RAA was made into a prototype and showed that WTBM is a potential substitute for natural tone wood as tone board material.

WTBM has many potential uses in acoustic applications. To fully understand and utilize these potential uses, numerous research opportunities should be pursued.

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APPENDIX A - PROJECT BRIEF

Personal Project Brief – IDE Master Graduation Project

Name student Ivo Neuman **Student number** 4,480,317

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Finding impactful applications for end-of-life wind turbine blade materials.

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Windturbines last for 20 to 25 years. After that, they are decomissioned. While a large part of the turbines can be recycled, the blades present a challenge since they consist of glass fiber composites which are difficult to recycle.
Material properties and applications for reuse of Decomissioned Windturbine Blade Material (DWBM) have been explored, yet finding relevant and impactful applications has proven to be challenging as wel.

Research goal:
Identify applications for DWBM that make as much use of its high-performance properties as possible.
Research questions:
1: What are the material properties of DWBM?
The findings of this literature study may warrant additional material property research.
2: Which applications for DWBM exist and how impactful are they?

Method:
A pilot study will be conducted using a material property driven method for identifying DWBM applications (Carrete et al., 2023). The results of the application finding method will be evaluated by making an experimental prototype, where I will focus on acoustic properties. The results of the pilot study will be combined with data generated by the research questions to identify an impactful and relevant application. The identified application will be evaluated with an experimental prototype.

The target stakeholders of the project are: Delft Technical University, DFS research group, Jelle Joustra, Israel Carrete, Magdalena Chmarra, Ivo Neuman. If a significant increase in sustainability is achieved, a larger societal impact is possible.
Source: Carrete, I. A., Joustra, J., & Balkenende, A. (2023). Circular Applications through Selection Strategies (CATSS): a methodology for identifying reuse applications for end-of-life wind turbine blades.

➔ *space available for images / figures on next page*

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Current windturbine blades are made from a material that is difficult to recycle, while a lot of them are being decommisioned. A large volume of high-performance and high embodied energy waste material is available. Very few applications that make proper use of the material's excellent properties are known. Next to this, applications that now require virgin materials with high embodied energy but could instead use DWBM are also rare.

Thus, to ensure that the applications for DWBM that I find are impactful they should:
1. Make as much use of the material's high performance characteristics as possible.
2. Replaces a (virgin) material with high embodied energy.
3. Require as little reprocessing of the original material as possible.

Combined, these solutions provide an opportunity to make windturbines more sustainable by extending the life of their materials and replacing a material with a high environmental impact. Moreover, the application finding method that is used will be evaluated which can provide new insights on its effectiveness. Finally, design criterea for making turbine blades easier to recycle can be recommended. Therefore, value is added for stakeholders Jelle joustra and Israel Carrete.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Investigate impactful applications of Decomissioned Windturbine Blade Material for the DFS research group within one hundred days.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Phase 1: Desktop research will be conducted to find information on windturbine blade material properties and current recycling applications.
The material application finding method by Carrete et al. (2023) will be used with a known comparison of material properties to familiarize with the method. Gaps in available information will be identified and experiments to fill this gap will be set up and carried out if needed.

Phase 2: The material application finding method by Carrete et al. (2023) will be used with a novel comparison of material properties, with a focus on acoustic properties for Distributed Mode Loudspeaker (DML) design. The found application will be evaluated using an experimental prototype.

Phase 3: Information gathered during previous phases, combined with the material application finding method by Carrete et al. (2023) will be used to find novel and impactful applications. A double-diamond will be used for conceptualisation. Ideation will be accompanied by brainstorming with groups. An experimental prototype will evaluate the results.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	31 Jan 2024
Mid-term evaluation	8 Apr 2024
Green light meeting	10 Jun 2024
Graduation ceremony	15 Jul 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✓
For how many project weeks	12
Number of project days per week	4,0

Comments:
Laptop repairability research project in February. February-April TA Repair! MSc elective one day p/w. March-April Drawing Human Figure elective.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

Motivation:
During the MSc programme a few opportunities for gathering experimental data presented itself. I found myself enjoying this process and I wish to expand on the competency of experimental data gathering. Next to this, prototyping has always been of interest to me. Competency in combining experimental data gathering with prototype evaluation is something that I would like to further develop. Furthermore, using resources in the most efficient way possible is something I have always found myself striving towards. This project embodies the resource efficiency that I always try to achieve, proving my interest and competency in this field.

Personal learning ambitions:

1. Gaining in-depth knowledge on material property evaluation.
2. Gaining in-depth knowledge on the effects of (mechanical) material properties on acoustic performance.
3. Experimenting with sound in anechoic environments.
4. Gaining real-life experience in the windturbine blade recycling process.