

TPMS Wall Patterns to Improve Acoustic Diffusion in Cultural Heritage

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Abstract

This study evaluates the potential of triply-periodic minimal surfaces (TPMS) as acoustic diffusers in cultural heritage contexts using three-dimensional FDTD simulations consistent with ISO 17497-2. Six TPMS geometries are analyzed, with their diffusion coefficients characterized across 100–5000 Hz and benchmarked against flat references. The results confirm frequency-selective behavior: Batwing is tunable in the low–mid range, Scherk's Tower performs best around 1.25 kHz, while Gyroid and Schwarz Primitive provide robust diffusion at higher frequencies (4–5 kHz). Costa and Diamond show a balanced response throughout. TPMS-based solutions are proposed for heritage spaces to improve speech intelligibility and musical clarity while preserving reverberation and historic aesthetics. The parametric models support tailoring diffuser designs to the acoustic needs of each venue, promoting reversible and visually compatible interventions.

Keywords

Acoustic Diffuser, Triply Periodic Minimal Surfaces (TPMS), Acoustic Cultural Heritage, Finite-Difference Time-Domain (FDTD)

1. Introduction

Since Schroeder's pioneering work on sound diffusers in 1975 [1], these surfaces have proved effective in improving spatial diffuseness and mitigating echoes and coloration [2]. Classical solutions include quadratic-residue and curved profiles [3], and more recent approaches involve metadiffusers [4]. Nevertheless, advances have been incremental, with only modest improvements beyond the early designs.

Triply Periodic Minimal Surfaces (TPMS), originally investigated for lightweight structures and additive manufacturing [5], offer smooth, curvature-continuous topologies that are attractive for architectural integration. They have shown promising behaviour in mechanics [6], heat transfer [7], and, more recently, acoustics [8, 9, 10]. Yet their potential as diffusers remains largely unexplored.

This work frames TPMS-based diffusion explicitly for cultural-heritage contexts. Historic churches, cathedrals, cloisters, theatres and museums often combine large volumes, reflective stone or plaster surfaces, and strict constraints on interventions. Heavy absorptive panels are generally excluded, since they modify the historic acoustic signature and are visually intrusive. Instead, diffusion is particularly valuable: it redistributes reflections while retaining reverberant energy, thereby balancing clarity with authenticity. Moreover, TPMS geometries can be fabricated in lightweight, reversible modules that are visually compatible with heritage interiors.

In such venues, the primary functional targets are speech intelligibility for guided tours, liturgy, and exhibitions, and, depending on use, clarity for early-music and choral repertoires. Objective

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descriptors and frequency weightings prioritise the 1–4 kHz range (with strongest emphasis around 2 kHz) [11, 12, 13], while low–mid bands between 250–500 Hz contribute to vocal fullness and warmth. Accordingly, diffuser designs that enhance scattering in 1–5 kHz, and optionally provide tunable support around 250–500 Hz, are particularly relevant in heritage acoustics [14, 15].

We evaluate the diffusion of representative TPMS with a 3D FDTD scheme aligned with ISO 17497-2, and we discuss how their frequency-selective behaviour can be mapped to heritage needs while preserving fabric and appearance. Section 2 outlines the 3D FDTD setup, Section 3 presents the TPMS set, Section 4 details the ISO-based methodology, Section 5 reports the main results, and the final section synthesises heritage-oriented recommendations.

2. Three-Dimensional (3D) Finite-Difference Time-Domain (FDTD) Simulation Technique

The FDTD method solves acoustic wave equations by discretizing space and time, enabling the simulation of sound propagation through complex geometries [16]. In this work, a full three-dimensional implementation is applied to analyze the diffusion of periodic structures such as TPMS, extending the two-dimensional framework reported by J. Redondo et al. [17].

Numerical stability requires that the time step satisfies the Courant-Friedrichs-Lewy condition in three dimensions:

$$s = c \Delta t \sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2} \leq 1. \quad (1)$$

The spatial resolution is also limited by the maximum frequency considered. While four cells per wavelength are sufficient for basic accuracy, at least ten are recommended for high precision [16]. In this study, grid spacing was chosen to ensure accurate results up to 5 kHz. To avoid spurious reflections at the boundaries, Perfectly Matched Layers (PML) were applied [18]. This combination allows us to model frequency bands of interest for heritage use with sufficient precision.

3. Triply Periodic Minimal Surfaces (TPMS)

A TPMS can be defined by an implicit scalar function $f(x, y, z)$. To transform the infinitely thin surface into a solid with thickness t inside a cubic cell of side a , the solid domain is expressed as:

$$|f(x, y, z)| \leq \varepsilon, \quad \varepsilon = \kappa \frac{t}{a}, \quad (2)$$

where $\kappa \in [1, 2]$ scales the threshold to the functional range of f . Using scaled coordinates $x', y', z' = \frac{2\pi}{a} \xi$ (with $\xi = (x, y, z)$) ensures periodicity over $a \times a \times a$.

Six TPMS were selected: Schoen’s Batwing, Scherk’s Tower, Gyroid, Diamond, Schwarz Primitive, and Costa Surface. Scherk’s Tower is periodic in two axes and extruded along the third, while the Costa Surface lacks a simple trigonometric implicit form and is usually defined parametrically or through Weierstrass data. Their inclusion offers both canonical and mathematically complex geometries for comparison.

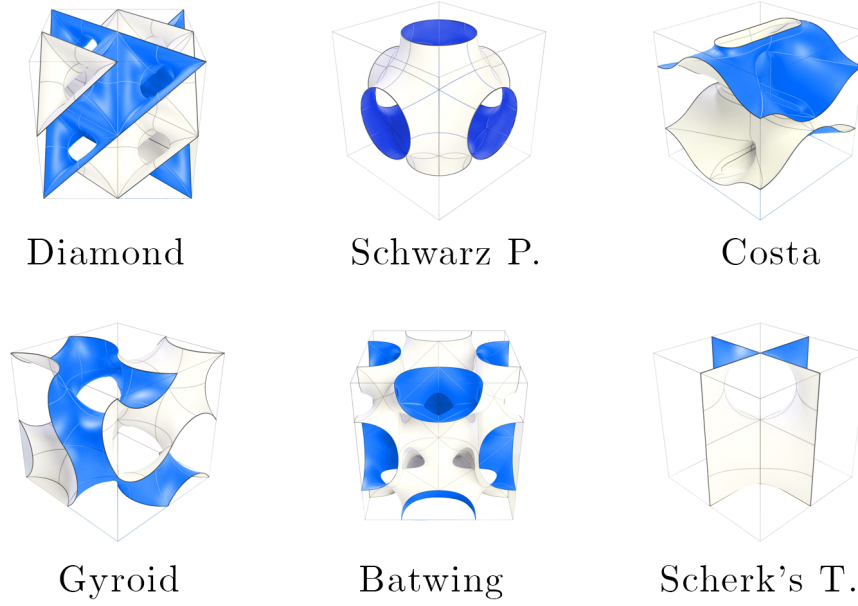


Figure 1: The six TPMS under study: Diamond, Schwarz Primitive, Costa Surface (up). Gyroid, Schoen's Batwing, Scherk's Tower (down).

4. Methodology

4.1. FDTD simulations and scattered field acquisition

To characterize the acoustic diffusion behavior, three-dimensional FDTD simulations were performed with a total-field/scattered-field (TF/SF) formulation. The excitation was a plane transparent source with Ricker wavelets centered at 250 Hz, 500 Hz, 1 kHz, and 2 kHz [19, 20]. These signals provide broadband coverage while minimizing low-frequency artifacts. PML boundaries were used to suppress reflections. This framework makes it possible to quantify time spreading, a phenomenon strongly linked to surfaces that promote sound diffusion [21].

4.2. International Standard ISO 17497-2

ISO 17497-2 defines the measurement of the diffusion coefficient using a goniometric setup in an anechoic or semi-anechoic chamber [22]. A loudspeaker and microphone rotate independently around the sample, capturing reflected responses at multiple angles. The diffusion coefficient δ quantifies how evenly energy is scattered relative to a flat reference surface, evaluated across frequency bands.

4.3. Model setup (Big Model)

To replicate the ISO 17497-2 standard procedure, a $3 \times 3 \times 1$ TPMS block was placed at the center of a cubic room with PML boundaries. The domain measured $7.00 \times 7.00 \times 4.20$ m with a PML thickness of 0.20 m. The TPMS diffuser had dimensions of $0.60 \times 0.60 \times 0.20$ m, and the measurement arc radius was 3.20 m. A rigid wall was imposed behind the diffuser. This setup mimics an anechoic-chamber environment at architectural scale and allows direct comparison with ISO procedures, ensuring that the simulated diffusion coefficients are interpretable in real-world measurement terms.

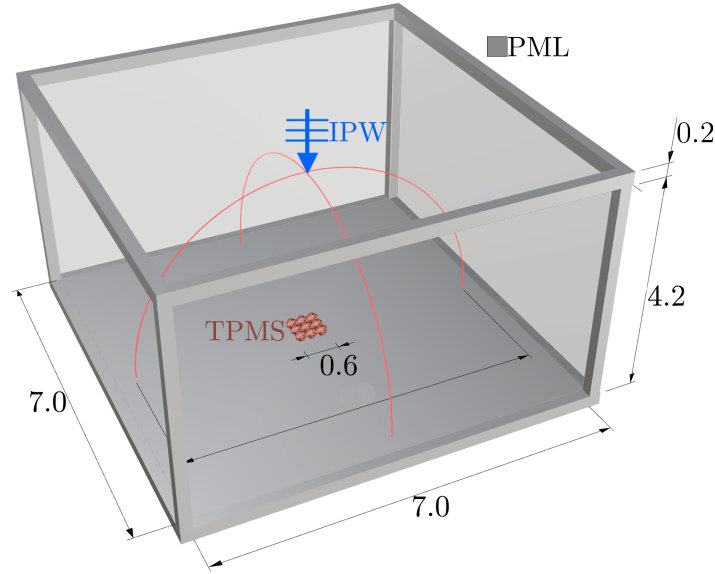


Figure 2: 3D FDTD model used to calculate the diffusion coefficient δ . a) Big Model with the three-dimensional goniometer represented with the two red arcs. An acoustic Incident Plane Wave (IPW) is the excitation. All geometric dimension units are meters.

4.4. Parametric modeling of TPMS-based solids

Using a *Grasshopper* visual scripting environment and the *Millipede* plugin, TPMS structures were generated via a customizable, three-stage isosurface modeling workflow. The procedure began with the creation of a single TPMS unit cell, which was then replicated to form a larger periodic lattice. Finally, the resulting mesh was thickened and converted into a solid model for subsequent application.

Step 1: The initial step involved defining a three-dimensional computational domain with boundaries from $-\pi$ to π along the x , y , and z axes, utilizing the *Construct Domain* and *Range* components. This domain was discretized into a uniform grid by setting a resolution parameter via the *ISOResSteps* input, which determines the number of subdivisions per axis. Selectable mathematical expressions for canonical TPMS types—including Schwarz P, Gyroid, Diamond, Scherk's Tower, and Batwing—were implemented. The *Millipede* plugin's isosurface component then interpreted these functions to produce three-dimensional meshes, allowing for the visualization and subsequent manipulation of the TPMS geometries.

Step 2: Following the generation of the base TPMS unit by the isosurface component, spatial tiling was accomplished using components such as *Domain Box* and *Box Array*. This enabled the periodic replication of the single cell along the x , y , and z directions to form an extended lattice structure.

Step 3: In the final stage, the mesh was solidified through an offsetting operation. A sequence of mesh-processing components (including *Align Vertices*, *Combine & Clean*, and *SubD*) were employed to refine the geometry, resulting in a clean, closed polysurface suitable for practical applications like fabrication or numerical analysis. Fig.3 illustrates, in its upper section, the mathematical formulations and the three-step workflow for TPMS generation, and below, an exemplary TPMS geometry created using the *Box Array* component with tiling parameters $x = 1$, $y = 3$, and $z = 3$.

Since the Costa Surface lacks a closed-form trigonometric implicit equation, as noted earlier, its generation necessitated an alternative methodology. By employing the MATLAB Engine API for Python alongside existing scripts for elliptic functions, the Costa Surface was first computed numerically within MATLAB. It was then integrated into the modeling workflow via a custom Python script that established a link with Grasshopper. This integration occurred at **Step 1** of the Grasshopper workflow, substituting the standard isosurface-generation phase used for conventional TPMS. From this point onward, the identical procedural steps—including spatial arraying and solidification—were applied to the Costa Surface geometry, ensuring its seamless incorporation into the overarching parametric design pipeline.

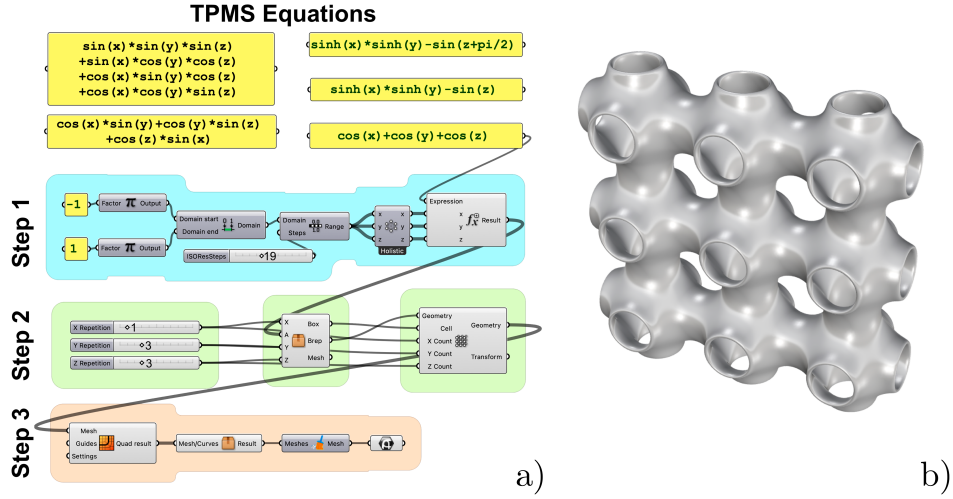


Figure 3: Three-step workflow for TPMS generation (a); an example of a generated TPMS surface (b).

5. Results

This section first compares the overall performance of the TPMS using the Big Model and then examines frequency ranges where their diffusion is enhanced or reduced.

5.1. Global comparison analysis

Because the structures are scalable, it is useful to relate their lattice constant a to acoustic wavelengths. For $a = 0.2$ m, the Bragg frequency is $f_{\text{Bragg}} = \frac{c}{2a} = \frac{343}{0.4} = 857.5$ Hz (with $c = 343$ m/s). Figure 4 shows the diffusion coefficient δ normalized against a flat surface, with average values across 100–5000 Hz also indicated.

Values below the black curved line in Figure 4 indicate focusing behavior, worse than a flat surface. On normalized average, values cluster around $\delta_{\text{avg}} = 0.2$: Costa, Diamond, and Gyroid reach about 0.25, while Scherk's Tower performs lowest with 0.17. Batwing shows strong variation, with a peak of $\delta = 1$ at 315 Hz but poor results near 630–800 Hz. Scherk's Tower has a peak at 1250 Hz but focuses in 500–1000 Hz. The Gyroid steadily increases above 0.8 at 4–5 kHz, and Schwarz P. shows consistent growth, exceeding 0.6 at 5 kHz.

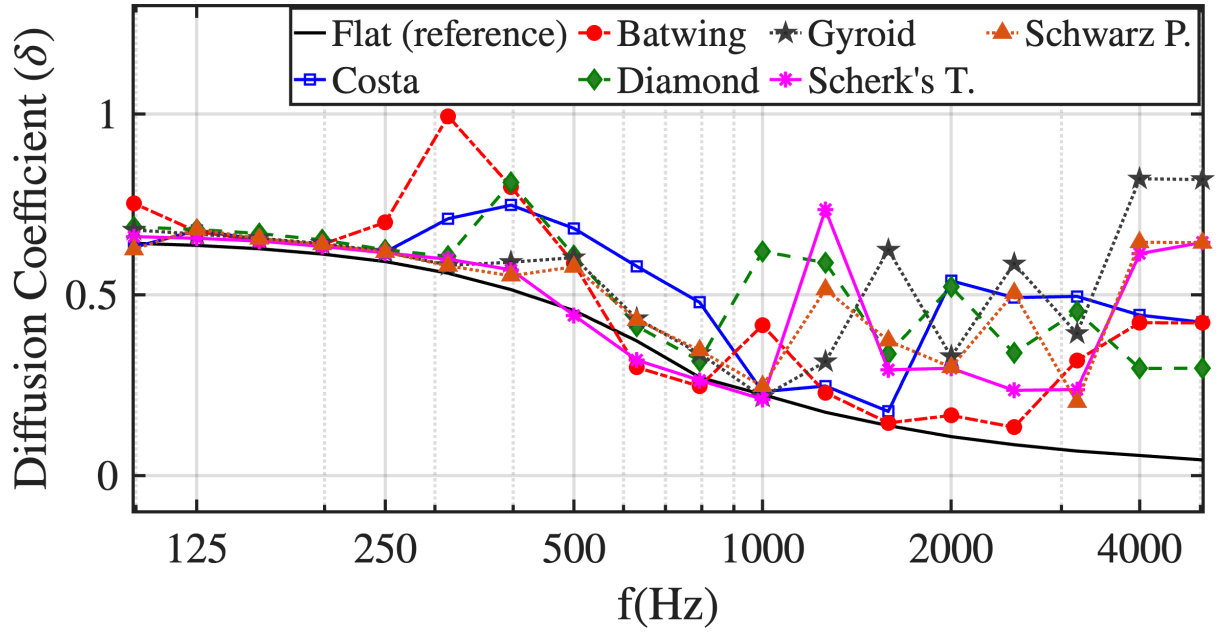


Figure 4: Diffusion coefficient δ compared to a flat surface, obtained with the Big FDTD Model and rigid backing in the 100–5000 Hz frequency range.

5.2. TPMS comparison analysis

Figures 5–6 present representative 3D polar scattering patterns for Batwing and Scherk’s Tower compared to a flat surface. The best and worst performance in particular frequencies is plotted. For Batwing, at 315 Hz the distribution is nearly hemispherical with $\delta \simeq 1$, while at 630 Hz forward scattering dominates and diffusion drops below the flat reference. The diffusion peak follows approximately $f_{\text{BatwingMAX}} \propto \frac{c}{a}$, allowing tunability by scaling the lattice constant. Scherk’s Tower achieves strong diffusion at 1250 Hz with eight secondary lobes distributed orthogonally and diagonally, but at 630 Hz it focuses energy with reduced diffusion.

The comparative analysis highlights trade-offs: Batwing is highly frequency-selective and tunable, making it suitable for targeted enhancement (e.g., choral warmth), whereas Gyroid and Schwarz P. are more broadband and thus valuable for general-purpose scattering. Costa and Diamond offer balanced but less extreme behaviour. Such contrasts are useful when matching TPMS designs to specific heritage needs.

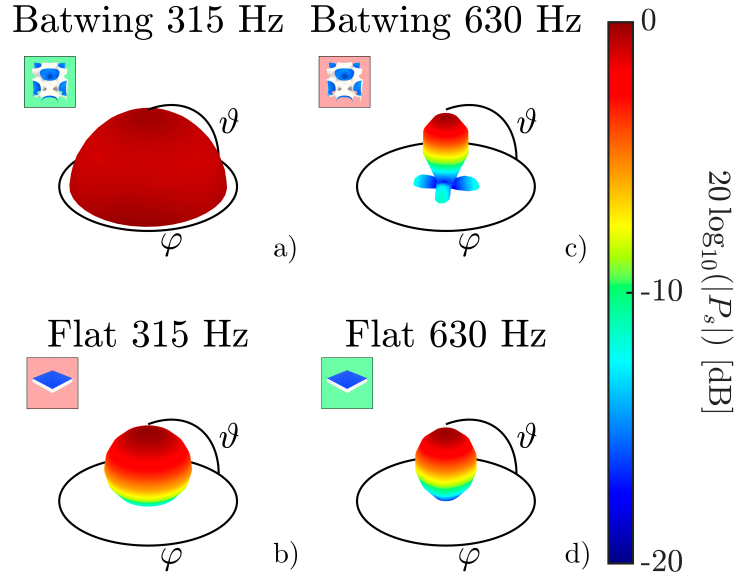


Figure 5: Three-dimensional polar scattering for Batwing TPMS and flat surface at 315 and 630 Hz.

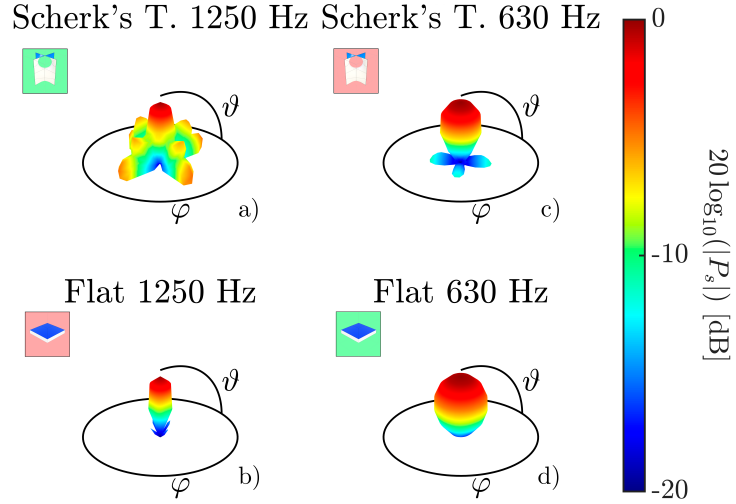


Figure 6: Three-dimensional polar scattering for Scherk's Tower and flat surface at 1250 and 630 Hz.

5.3. Discussion

Implications for cultural heritage. In heritage spaces, diffusion is often preferable to added absorption because it preserves reverberant character without compromising fabric or appearance [14]. Priorities typically include: (i) speech intelligibility for tours and liturgy, with greatest weight between 1–4 kHz [11, 12, 13]; and (ii) optional support of vocal warmth around 250–500 Hz for choral/early music. Mapping our findings to these bands suggests:

- *Speech clarity (1–5 kHz):* favour **Gyroid** and **Schwarz P.** for high-band diffusion; **Scherk's Tower** can target the lower end of this window (around 1–1.25 kHz).
- *Vocal warmth / low-mid support (250–500 Hz):* use **Batwing** tuned via lattice periodicity a . The peak scales approximately as $f_{\text{Batwing}} \approx 0.1837 c/a$. For design targets: $f = 500 \text{ Hz} \Rightarrow a \approx 0.126 \text{ m}$; $400 \text{ Hz} \Rightarrow a \approx 0.158 \text{ m}$; $315 \text{ Hz} \Rightarrow a \approx 0.200 \text{ m}$.
- *Broadband, visually uniform scattering:* **Costa** or **Diamond** when a balanced response and visual integration are prioritised.

In practice, heritage applications demand not only acoustic efficiency but also compliance with conservation principles [15]. TPMS modules could be fabricated in lightweight composites or wood,

mounted reversibly, and even integrated into removable exhibition panels. Future work should combine parametric optimisation with architectural surveys of heritage interiors, aiming at site-specific diffuser placement that enhances clarity while safeguarding authenticity.

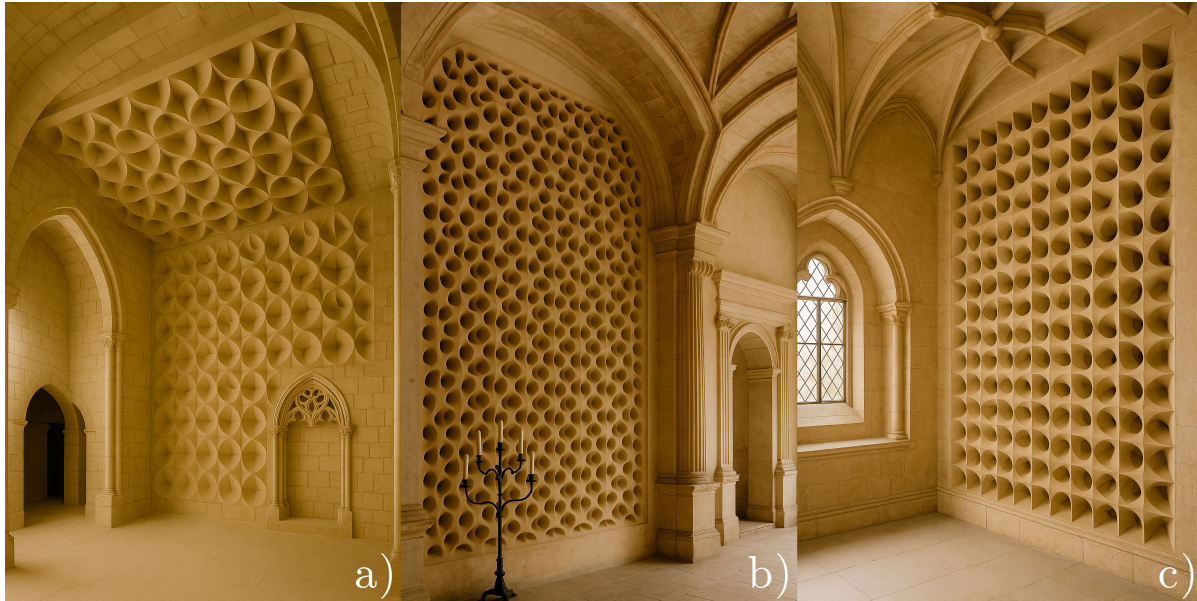


Figure 7: Examples of TPMS patterns applied to Cultural Heritage. a) TPMS panels in wall and ceiling. b) and c) Examples of embedded TPMS walls.

6. Conclusion

This study assessed the diffusion performance of six TPMS using a 3D FDTD workflow consistent with ISO 17497-2. We confirm frequency-selective scattering: Batwing exhibits a tunable low–mid peak (e.g., near 315 Hz with rigid backing), Scherk's Tower shows strong diffusion around 1.25 kHz, while Gyroid and Schwarz P. trend upwards at higher bands (4–5 kHz). Costa and Diamond provide broadly moderate diffusion across the spectrum.

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Author Declarations

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration on Generative AI

The authors did not use Generative AI to create, analyze, or interpret the scientific content of this manuscript. Grammarly was used solely as a writing-assistance tool to improve grammar, spelling, clarity, and sentence structure. After using Grammarly, the authors carefully reviewed and revised the manuscript to ensure the accuracy, originality, and integrity of its content. The authors accept full responsibility for all material presented in this publication.

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