A CEILING CASE STUDY INSPIRED BY AN HISTORICAL SCALE MODEL

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1 ABSTRACT

A scale model of a portion of the Abbaye de Saint Germain-des-Prés, conserved in the *Musée des arts et metiers* in Paris, exhibits a somewhat unique ceiling design, with exposed beams forming a type of spider web pattern. This design allows for a large flat span to be constructed using only small length beams. A historical and acoustical research effort was launched in parallel to investigate this interesting structure. Did it exist, or was the 1:25 model, constructed in 1884, an architectural and structural study exercise? The room has been reputed by some to be the location of the 1792 Revolutionary Tribunal in Paris. The form visually resembles a Fresnel lens. Could this design have an acoustic function? This study presents measurements performed in the historical scale model as well as numerical simulations based on the models geometry. Results show a consistent trend with the ceiling acting as a focusing element. Various historical elements are also presented, collected from various sources from more than a century ago. Parallels of the architectural concept are also made to other historical designs, as well as a modern architectural design study.

2 CREATION & HERITAGE

This study is part of a more general project concerning the understanding of the acoustics within a very special type of structure, which is at the core of the architectural and artistic project called *Woodstacker*[1], launched in 2004. This new building system, based on "stacked laminated" timber structures, showcases contradictory acoustics phenomenon in lamella ceilings. In the early 30's, lamellar timber structure like those of F. Zollinger[(a)] were used for public rooms (churches, exhibition halls, sport halls, etc.) because of their good acoustic properties[2] combined with their flexibility. The apparent wooden lamellas of the structure were supposed to diffuse sound and reduce reverberation time.[(b)] In the *Woodstacker* system, the special geometrical pattern of the lamellas seems more to focus the sound. The result is a passive amplification at particular positions within the structure. This phenomenon, which can offer interesting perspectives in some cases, like small auditoriums or home studios[3], needs to be better understood and managed for future uses.

The architectonical type of structure under study is a solution to a geometrical problem of how to cover a large area by stacking small pieces of wood without the use of glue or nails. The result is a bottle shape three-dimensional rose window figure (see drawing Figure 1(a) and photograph Figure 2(a)). In search of anteriority for that building system, it was found in French carpentry treaties that this construction principle was intended to be used for polygonal ceilings, since the 18th century. But, as far as we were able to ascertain, no examples of such a construction remain. The recent discovery of a lamellar polygonal ceiling model of this type (see drawing Figure 1(b), photographs Figure 2(b) and Figure 7(b)), in the collections of the *Musée des arts et métiers,* Paris, offered an opportunity to study this acoustic phenomenon and with it a novel approach in the use of historical

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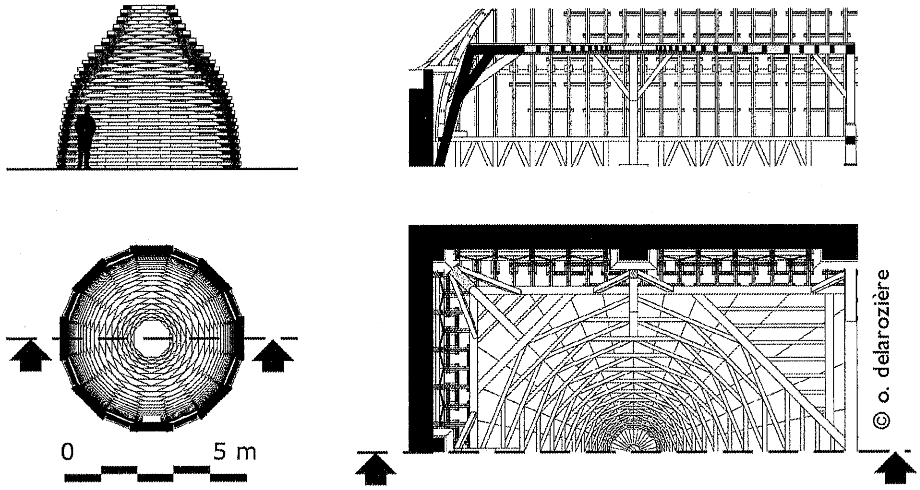
(a) Friedrich Reinhart Baltasar Zollinger (1880-1945), Engineer and Town Building Advisor, developed a lamella system called *Zollbau* widely used in Europe and America for arched roofs.

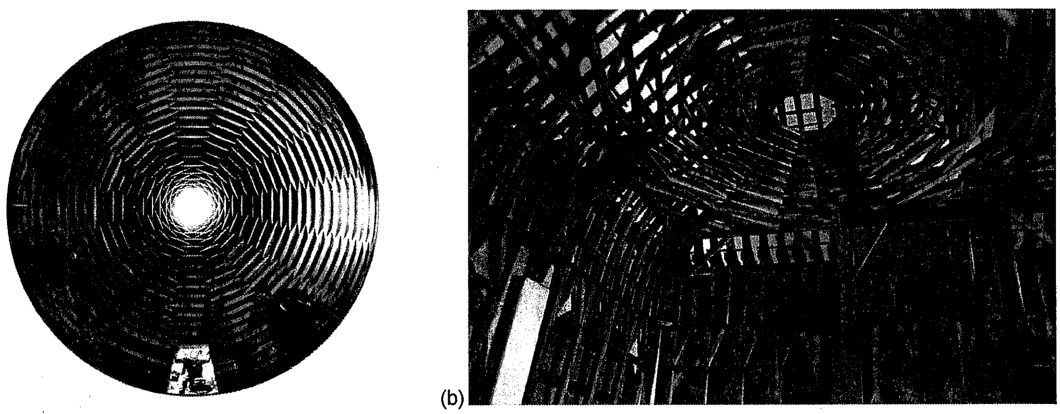
(b) « Signalons la bonne résistance au feu de ces charpentes et leurs qualités acoustiques (diminution de la réverbération), lorsqu'elles sont laissées apparentes. » in 2, p. 63.

models for retro-engineering the past in order to inform the future. This modest study is intended to be the starting point of a work that aims to link art, science, and heritage.



(a) (b)

Figure 1, Section and reflected ceiling plan of (a) A *Woodstacker* stacked lamella timber cupola. Champ-au-Beau, France, 2010 and (b) the roof frame of Saint-Germain-des-Prés. Musée des arts et métiers inv. 10979. Scale: 1:200. © O. D.



(a) (b)

Figure 2, Interior photograph of (a) *Woodstacker* stacked lamella timber cupola and (b) 1:25 scale model of the roof frame of Saint-Germain-des-Prés. Musée des arts et métiers inv. 10979. Dimensions: 64 x 80 x 84 cm. Photo © O. D.

3 HISTORICAL INVESTIGATIONS

3.1 A 19th century model

The model at the center of this study entered the collections of the *Musée des arts et métiers* in 1884. It was considered to be a reduce scale model of a roof frame *à la Philibert de l'Orme*. In actuality, this model consists of a combination of two different frames. One is a round arched roof frame *à petit bois*, a lamellar timber framing system developed by the French architect Philibert de l'Orme (c. 1514 – 1570), first published in 1567[4]; the second is the polygonal ceiling under study. These two structures form the extrados and intrados of a very particular cupola. Prior to this study, very little was known about this object, with the museum exhibit label stating simply: « Charpente de l'abbaye de Saint-Germain-des-près, XVI^{e} siècle. Modèle réalisé au 1/25 réalisé par B. Minard,

1884. Inv. 10979 ». Was it an un-built architectural project? A master construction carpenter's work of art? The model of an historical building?

In a letter found in the museum archives, Beloni Minard (1830 - ?), the carpenter and author of the model, explains that this work, shown at the French Central Union of the Decorative Arts in Paris in 1884 was a model of a building which belonged to the Abbey of Saint-Germain-des-Prés which was destroyed to make way for the Boulevard Saint-Germain in 1875.[5(c)] The date and location appeared to be correct as the final phase for the opening of the Boulevard Saint-Germain in Paris was decided in 1874 by the post-Hausmanian administration. Fortunately, the destruction works were followed up by Théodore Vacquer (1824-1899), inspector of the *Service historique de la ville de Paris*, and a report of the *Société de l'histoire de Paris et de l'Ile-de-France*, dated the 14th December 1874,[6] confirmed the existence and location of this impressive building[(d)] as well as providing the reference of a journal article which included images of this construction.

3.2 A French revolutionary tribunal room?

This article entitled « *Le tribunal de l'abbaye* »[7] (literally the Abbey's tribunal), in *Le Monde Illustré,* written by Auguste Lepage (1835-1908) is richly illustrated with three art prints which represent, in a very realistic manner, the roof frame and the "so called room where should have been held the revolutionary tribunal" (Figure 3(a)). This title made reference to the bloody events of September 1792 where a thousand supposed counter revolutionary people (priests, aristocrats...), confined in the military prison of the Abbey close to this room, where quickly judged and executed by the French « *régime de la Terreur* ».

Unfortunately, this designation of "tribunal" was unfounded because, as Theodore Vacquer mentioned in December 1894, the building probably didn't exist at this time.[6(e)] It is still unclear what this spectacular room of 13×13 meters with a ceiling height of 10 meters was used for, but the testimony of the very special sensation this place has given to its visitors leaves us wondering what could have been the acoustic ambiance inside.

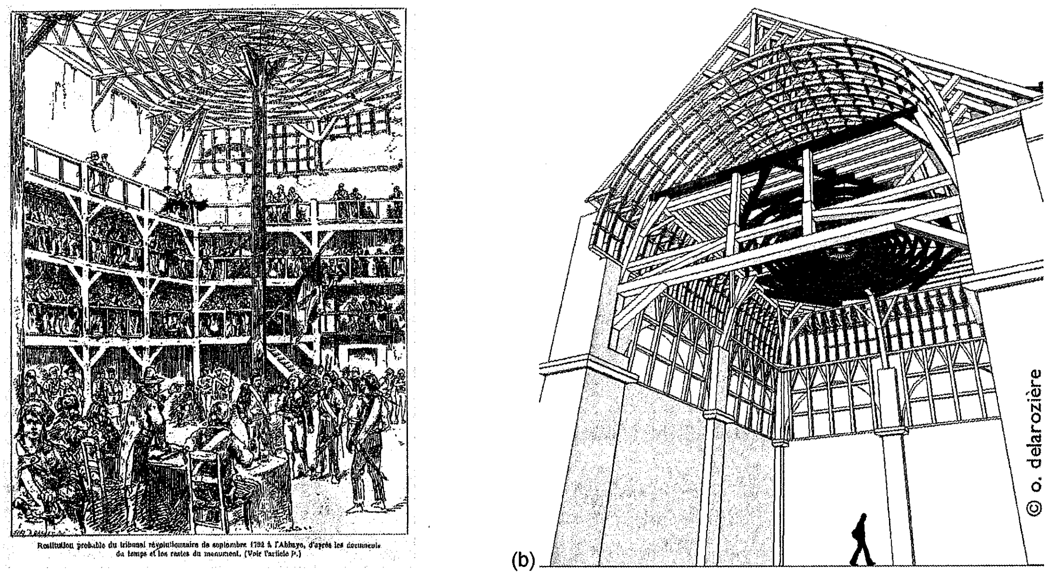
> To this room vested to meditation and prayer are linked bloody memories. It is there that was sitting the famous court presided over by the usher Maillard, during the September 1792 massacres [...]. Massive pillars supported a roof frame, which was a wonderful construction. This frame, rounded in a dome shape was made from Spanish chestnut, no nails were used and the thousand pieces that composed it were only fixed up by pegs [...]. This wonderful frame [...] is going to be dismembered and transform into firewood. Shouldn't we have transported it to one of the building constructed by the State or the City and avoid the destruction of a truly remarkable work.[7] (p. 374)

No one took up the challenge to conserve this framework. It was destroyed in 1875 and it was not until 1884 and the eighth exhibition of the French Central Union of the Decorative Arts, that it was reborn in the form of a reduced scale model, under the signature of Beloni Minard. This model was presented at the exhibition along with plans which were also fortunately conserved in the *Musée des arts et métiers*.

(c) « En 1884, Exposition des Arts Décoratifs, j'exposais un Comble à la Philibert Delorme couvrant l'ancienne Abbaye Saint Germain des Prés que j'ai relevé sur place en 1875 lors de la démolition pour le passage du Boul[e]vard Saint-Germain » in 5.

(d) « M. Vacquer entretient aussi la Société d'une charpente fort remarquable qu'on peut encore visiter ces jours-ci dans une maison de la rue Gozlin, ancienne dépendance de l'abbaye de Saint-Germain-des-Prés. Certains architectes ont voulu voir dans cette charpente une œuvre de Philibert Delorme, mais les anciens plans de l'abbaye prouvent qu'elle est loin de remonter au XVIe siècle, et qu'elle a seulement été construite suivant le système inventé par Delorme et appliqué à la Halle aux Draps en 1783 par les architectes Legrand et Molinos » in 6, p. 165.

(e) « À en juger par le plan de Verniquet levé de 1774 a 1789, n'existait pas encore à cette époque. C'est à tort qu'on a vu dans le bâtiment de la rue Gozlin la salle où auraient été rendus les arrêts de mort qui précédèrent les massacres de septembre 1792 » in 6, p.165.



(a) (b)

Figure 3, (a) Legend translates to: "Likely restitution of the revolutionary court in September 1792 at the Abbey." Reproduced from Lepage[7], p. 384. (b) Numerical model based on plan and scale model from Beloni Minard. Highlighted elements indicate those used in acoustical model study. © O. D.

4 ACOUSTICAL STUDIES

A series of acoustical studies have been performed on the framework in question. These studies were performed in several stages of increasing complexity: 2D simplified ray tracing, 3D particle tracing, 3D numerical room acoustic simulation, as well as measurements in the actual scale model.

4.1 Digital models

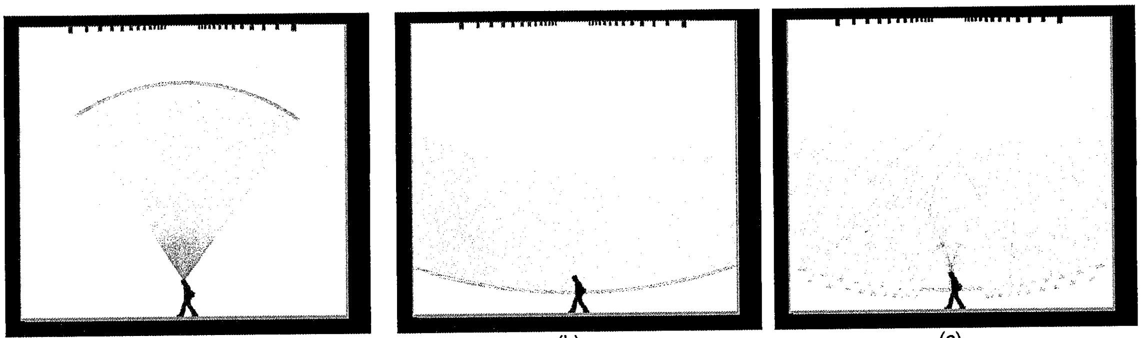
Without the high accuracy of Minard's work it would have been impossible to digitally rebuild this room. In a way, Minard's work functions as a facsimile of architecture[11] and the computer model is a final attempt to rehabilitate this building. A rendering of the complete numerical model is presented in Figure 3(b). Simplified surface models were done for acoustical simulation purpose. In the early phases of the study, the true height of the ceiling had yet to be determined, and as such the ceiling height was adjusted to conform to that of the scale model in all numerical simulations. Discovery and inspection of the drawings and actual model shows that the cross-section size of the framework elements is 7×7 mm at the center, increasing to 13×13 mm at the edge (see Figure 1(b)). This equates to 17.5 cm to 32.5 cm at full scale, or one wavelength at 1960 to 1086 Hz respectively.

4.1.1 2D Simplified Ray tracing

From the computer architectural reconstruction, a section was cut through the axis of the structure, as shown in Figure 1(b), and the beam elements where identified. The simplified section of the model was then used in a simplified geometrical ray tracing algorithm (*2Draytrace*, developed in the MatLab environment) to examine the effects of the presence of the exposed ceiling frame. The ceiling height was adjusted to conform to that of the scale model. Results of this simulation, shown in Figure 4, indicate a focusing effect of the ceiling beams for a central source position. Additional examples showed similar results for eccentric source locations, with the return paths following the source position.

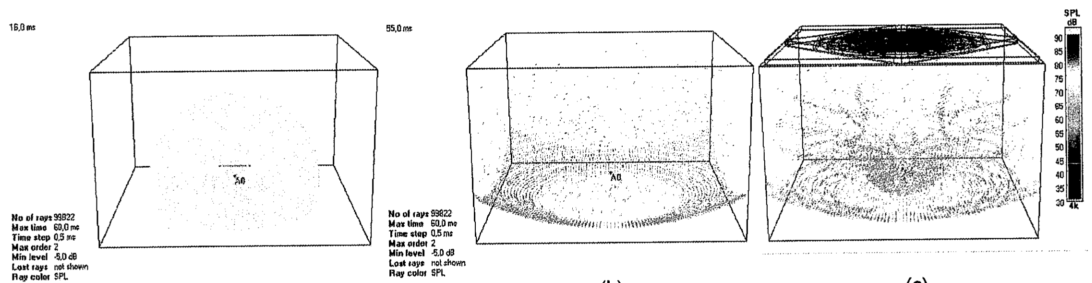
4.1.2 3D Ray tracing

Inspired by these initial results, a similar study was performed using a 3D ray tracing visualization approach. The 3D geometrical model was analyzed with CATT-Acoustic using the "Time trace" option. All surfaces other than the ceiling under study were considered totally absorbing. The results, as shown in Figure 5, are similar to those found in the 2D study, with a focusing return effect very evident to the source position.



(a) (b) (c)

Figure 4, Simplified 2D ray tracing visualization showing the (a) incident ray paths, and reflected ray paths for a (b) flat ceiling, and (c) the exposed ceiling beams.



(a) (b) (c)

Figure 5, "Time trace" 3D ray trace visualization [99822 rays, 0.5 ms time step] at time step (a) 16 ms, and 55 ms for the (b) flat ceiling, and (c) the exposed ceiling beams.

4.1.3 3D Room acoustics analysis

Inspired by the results of the simplified analysis visualization methods, the model was then used for a full impulse response analysis using the same acoustic conditions so that only the ceiling was considered as contributing acoustically. Due to the overall absorptive nature of the model, essentially a suspended ceiling in free-field, the majority of room acoustical parameters are not pertinent and difficult to interpret. However, as inspection of Figure 5 indicated at time of arrival of the reflected energy from the exposed ceiling frame on the order of over 50 ms, the clarity parameter seems a viable choice for examination. The parameter **C-50** is a ratio of the early energy (up to 50 ms) to the late reverberant energy (from 50 ms onwards), used to evaluate the clarity of speech.[8] The results of this comparison are shown in Figure 6. While the absolute **C-50** values are not really relevant, due to the absence of the rest of the architecture in the simulation, the differences between the two ceiling models is clear. The arrival of the focussed ceiling reflections from the exposed beams, with significant energy, is sufficient to greatly affect speech clarity in the space.

Additional studies of this nature, with the inclusion of the other acoustical surfaces in the room, would be beneficial in understanding the perceived acoustics of the space. At present, the function, outfitting, and occupation of the room is still under study and, as such, it would be premature to make any additional suppositions of the room's architectural acoustic design.

It is finally noted that the author's understand that this type of investigation, examining the acoustic effects of small surface in a non-diffuse sound field, is not what the chosen software was intended to be used for, and that this study is using the tool in a very extreme case. Nonetheless, the different numerical studies seem to offer results that are not counter-intuitive.

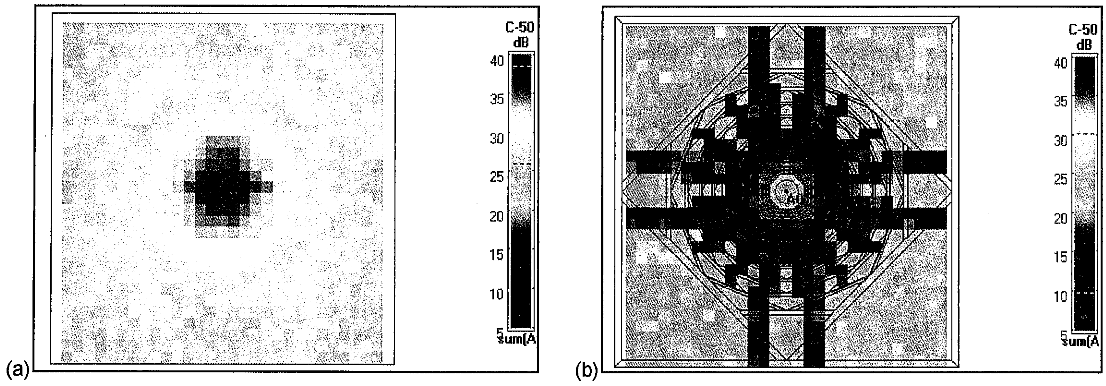


Figure 6, Numerical prediction of C-50 (dBA weighted sum) [1000000 rays (adapt), 1000 ms] for (a) flat ceiling condition and (b) the exposed ceiling beams.

4.2 Physical model

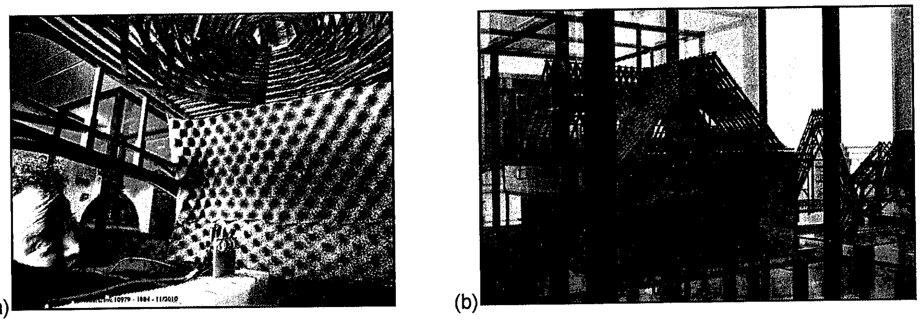
In an effort to further examine the acoustical impact of the ceiling structure, and in order to avoid the potential effects of numerical simulation approximations in this extreme case study, it was decided to attempt to make acoustical measurements in the actual physical scale model. The use of scale models for acoustical research is a common practice in acoustics for many years.[9,10] These results can then be interpreted in parallel to those of the numerical simulations.

The scale model under study is only a portion of the actual building, with an attention to the different frame constructions for visual inspection. As such, two of the four walls are absent. In addition, the ceiling material which would be above the exposed framework was not apparent. Finally, as was determined at the end of the study, after examining all the archives, the scale model construction represents only the upper portion of the building, and the actual floor level would have been lower. In order to conform to the numerical studies, and to focus attention solely on the acoustical effect of the ceiling frame, all non-ceiling surfaces were acoustically treated. Each wall was covered with acoustic foam, including the two open side walls. The floor was covered with an absorbing blanket. A plexiglass panel was installed above the framework to provide a closed ceiling. A cardboard panel was fitted to the underside of the framework to represent the flat ceiling comparison condition.

Impulse response measurements were obtained along the centreline of the ceiling, with the source placed at the centre of the framework structure, as was the case in the numerical studies. The source was a 1 cm diameter dome tweeter (not including the surround), directed towards the ceiling, and power amplifier (Samson Servo 120a). Four microphones (DPA 4060) were used with a multichannel audio interface (RME Fireface 800) at a sample rate of 192 kHz. While this equipment is not usually considered standard measurement grade, the different elements have been found to have significant performance above audible frequencies and have outperformed more traditional measurement configurations in terms of signal-to-noise ratio. A signal-to-noise ratio of 60 dB was easily obtainable in this measurement setting. In addition, attention of this study will concentrate at on frequencies pertinent relative to the beam size. In the model, the beam depth is comparable to one wavelength at 25 kHz, or 1 kHz at scale 1:1.

The four microphones were spaced at 1 cm intervals on a single movable support. The microphone array was positioned using a graduated guide to ensure the correct spacing throughout the measurement starting at a distance of 4 cm from the source axis (see Figure 7). A total of 24 microphone measurement positions were used, spanning the half-width of the model. Converting to full scale dimensions, this equates to positions from 1 to almost 7 meters from the source.

Impulse response measurements were made using in-house all-scale measurement software (*IRA*, developed in the MatLab environment). Measurements were made using the exponential sweep-sine excitation method.



(a) (b)

Figure 7, (a) View of the interior of the scale model, microphone array, and source being prepared for acoustical measurements showing installation of added acoustic damping materials. (b) View of the exterior of the scale model. Musée des arts et métiers inv. 10979.

In order to isolate the acoustical effect of the ceiling from other elements of the model, the impulse responses (IR) were windowed after correction for air absorption as a function of temperature and relative humidity was applied. For each IR, the direct sound arrival time, t_0, was detected using a relative threshold of -3 dB (threshold level relative to the maximum of IR). Inspection of the measurement series resulted in the observation that no reflections arrived within the first 0.9 ms. The longest possible reflection path from the source to the ceiling and the farther microphone was measured and was equivalent to 3.2 ms, resulting in a windowing of the responses from (t_0 + 0.9 ms) to (t_0 + 3.2 ms). Windowed responses were then filtered in 1/3rd octave bands.

Results for frequency bands 800 – 1600 Hz are shown in Figure 8 for the flat ceiling and exposed framework conditions, with levels normalized to the nearest flat ceiling condition position. A 5th order polynomial fit is shown for both conditions, as well as a linear fit for the flat ceiling condition. The results for the flat ceiling condition are close to linear. It is noted that this analysis examines only the energy of the ceiling reflection component, and not the direct component. As such, the direct distance to the source is not the propagation distance of the reflections and a $1/r^2$ behavior would not be expected from these values. It is clearly evident that there is reinforcement close to the source in the exposed framework condition, with the strongest effect in the 1 kHz band. The focusing effect drops off rapidly, with adjacent sound pressure levels exhibiting lower sound pressure levels when compared to the flat ceiling condition. This seems reasonable, as the total energy must be conserved, and the focused energy must come from somewhere. Finally, at the border positions, located near the wall, an increase in sound pressure level is observed for both conditions relative to the linear fit model of the flat condition. These end effect results, and the measurement variability, may be due to edge effects near the added wall absorption, the ineffectiveness of the absorption used, the fact that some transversal structural elements were left exposed (see Figure 7(a)), effects due to other ceiling elements not included in the numerical model (see Figure 3(b)), or the lack of ideal omnidirectionality for the source and microphones at 25 kHz.

5 CONCLUSION

This work presents a historical, architectural, and acoustical study inspired by history as well as modern architectural explorations. This study is centred on various interests concerning a 19th century reduced scale model, by Beloni Minard, which has preserved the memory of a rather remarkable piece of architectural framework.

Through the use of numerical modelling and measurements, this study has attempted to bring new life to both the model, and the history of the building it represents. Focussing on the acoustical aspects of the somewhat unique architecture, both numerical models and the actual 19th physical model have been studied using modern methods, revealing prominent focussing effects for frequencies whose wavelengths are comparable to the various beam cross-sections.

The authors hope that this virtual restoration of a "living" carpentry masterpiece of a 19th century museum will contribute to finding new means to conceive future works, such as new lamella structures like *Woodstacker.* The authors hope that they have participated, in some way, to the dream of the carpenter Beloni Minard, and other contemporary people, to restore this building of an architect still to be determined. This study is dedicated to these artists.

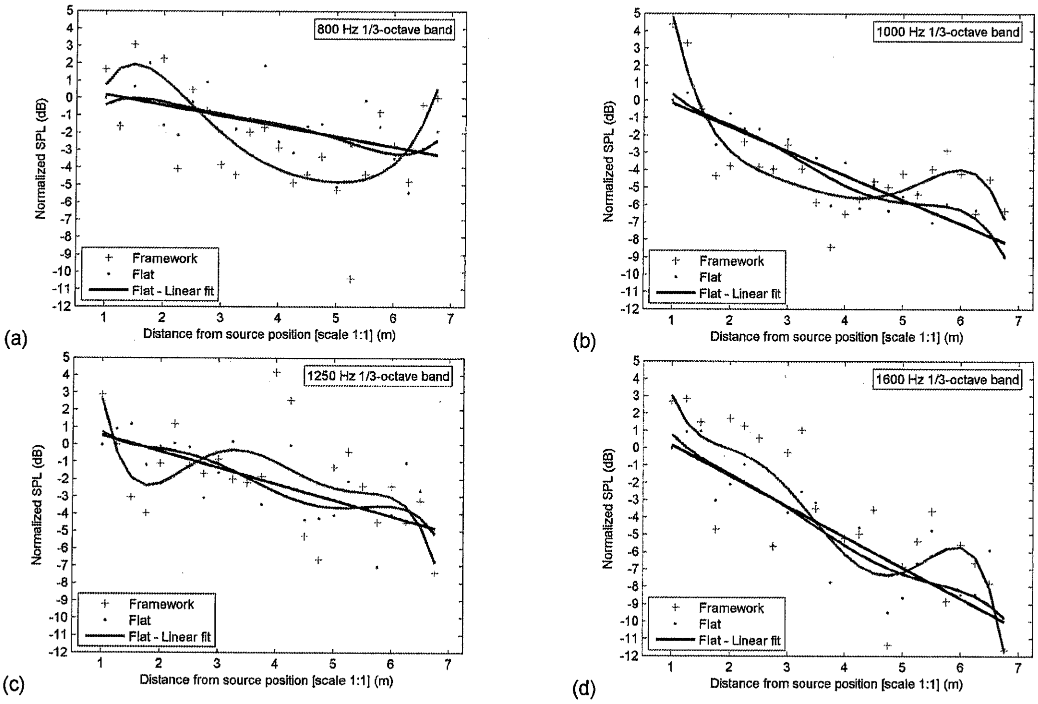


Figure 8, Measured normalized sound pressure level (1/3rd octave bands) for exposed framework ceiling beams and flat ceiling conditions. 5th order polynomial fits are shown for both, as well as linear fit for flat ceiling. Data scaled to scale 1:1 values.

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