AUDITORIUM OF THE MORGAN LIBRARY, COMPUTER AIDED DESIGN AND POST-CONSTRUCTION RESULTS

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1 INTRODUCTION

The auditorium for the enlarged Morgan Library & Museum in New York, by architect Renzo Piano Building Workshop, was conceived as a world class 300-seat concert and recital hall worthy of the library's music collection. Constructed as part of the Library's renovation on 37th Street in New York City and situated below ground between existing structures, the design of the small hall was extremely restricted with regards to dimensional freedom. In order to create the desired acoustics in a relatively narrow and boxy footprint, the design concept makes use of a large number of wooden wall and ceiling panels and a variable height stage reflector. A thorough study using computer simulations was carried out to optimize panel geometries and orientations while keeping within the aesthetic guidelines of the architect. The flexibility of the simulation tools allowed for several options to be investigated. The architectural scheme of the hall is simple and elegant, with angled wall panels and curved ceiling reflectors. Opened in 2006, the hall has been well received, providing a full acoustic with high clarity and envelopment. Post-opening measurements have been made and show good agreement with predicted results.

2 THE MORGAN LIBRARY AND ITS AUDITORIUM

2.1 Project background

In addition to an exquisite collection of drawings, The Morgan Library & Museum owns a world-class collection of manuscripts and musical autographs, and the client's brief for the renovation and extension of the museum's premises included the request for a high-class Auditorium for both music and speech. Renzo Piano Building Workshop was the architect for the renovation and extension project, and Kahle Acoustics, in collaboration with Harvey Marshall Associates, New York, was the acoustician for the project. In order to not overshadow the exquisite historic buildings, the Auditorium was located underground, and had to be carved out of the New York granite.

The available space on site, between the foundations of existing buildings, was extremely limited, and as a consequence the width of the hall had to be limited to less than 10.5 m – certainly a challenge even for a relatively small Auditorium, but we believe part of the acoustic success of the hall as well. The bottom slab is located about 14 m below street level.

Figure 1: *View of the Auditorium during construction: the hall is carved out of the rock between neighboring buildings.*

2.2 Auditorium Design

Due to the site requirements, with limited width and height meaning costly excavations, obtaining a sufficient acoustic volume was of course a first concern. It was possible to achieve a maximum height of 10 m (interior dimensions), and an acoustic volume of approximately 2038 $m^{3.}$ The shape of the hall is a shoebox, both because the available space between the buildings was of that shape, and for aesthetic consideration. From the onset of the design, the Auditorium was to be a "jewel", reflecting the many miniatures and marvels housed by the Library, and the interior finishes were to be wood panels.

The architectural look of the hall was to be simple and elegant. A wooden panel design was proposed for the wall finish, and curved wooden ceiling panels were incorporated for visual and acoustical shaping. In order to create enhanced lateral reflections, the original design proposed three-part bowed ceiling panels, angled in long section and curved in the short section. This can be seen in the photos of the architectural model, build by Renzo Piano Building Workshop during the early design phase. For both technical and acoustic reasons, a technical balcony was added around the stage and extending over the front part of the audience area. This balcony creates strong (mainly lateral) reflections back to the performers as well as to the audience members located in the front part of the parterre. The audience is seated on a single, rather steeply raked, parterre, both for sightlines and because the entrance of the underground Auditorium needed to be easily accessible and well connected to the new Foyers.

In order to avoid negative effects of the parallel side walls and the reduced width, it was decided to exploit the wall panel design of the architect to provide some shaping to the room, while remaining confined to the strict shoebox geometry.

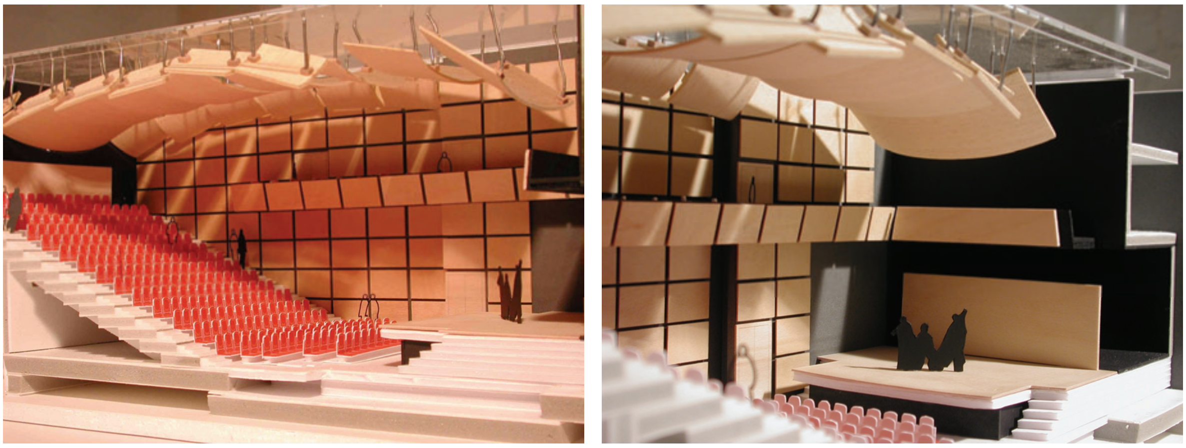

Figure 2: *(Left) Architectural model during design phase, showing the steeply inclined seating area, the technical balcony (with flat balcony fronts) and the three-part ceiling panels. (Right) View of the stage in the architectural model (early design phase). Ceiling panels are strongly curved in short section, with a relatively large center part and the two side parts angled to create enhance lateral reflections. The stage is extendable in size, proposing a small, medium or large stage (medium stage size shown in model).Model by Renzo Piano Building Workshop.*

A computer model study based on this model and the corresponding plans and sections was undertaken. A parametric model was created using CATT-Acoustic (v7.2i). Using this model, the orientation of every wall panel could be modified (individually or in groups). The orientation and curvature of the ceiling panels was also easily varied.

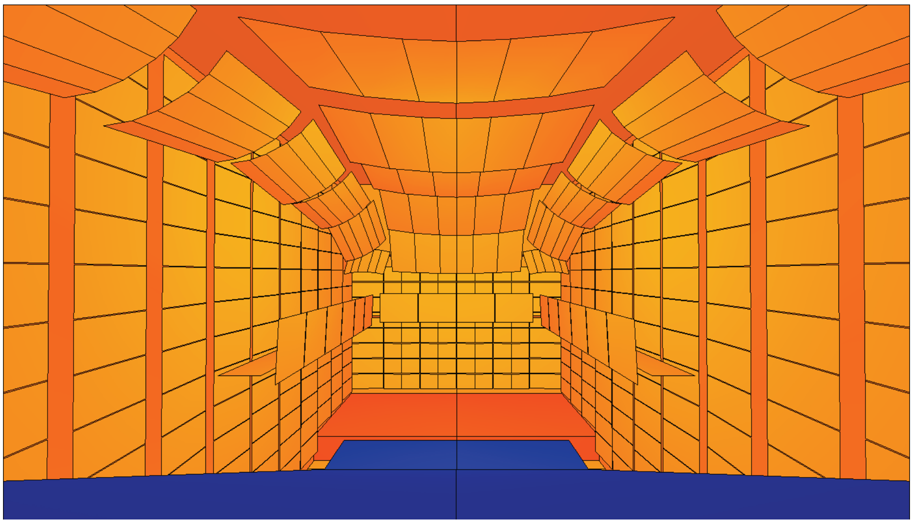

Figure 3: *Interior view of parametric room acoustic model showing ceiling and wall panels.*

The conclusion of the study was to have a positive horizontal angle for the front (stage) half of the panels, while the rear hall panels were angled in the opposite direction creating a projecting stage environment yet a reverse fan shape in the audience chamber. After collaboration with the architect on the details, it was decided that the walls panels were set at an angle of +6 degrees around the stage and -3 degrees around the audience chamber. V-shaped panels were used for the stage wall as well as the back wall of the Auditorium.

A variety of ceiling panel curvatures was examined from convex to concave. The height and positions were also studied for optimal sound distribution. The following figure shows some examples.

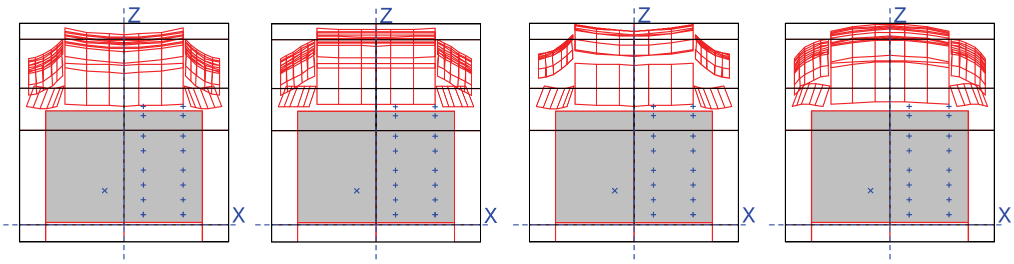

Figure 4: *Examples of curvature variations for the ceiling panels.*

While the study was underway, Renzo Piano finally decided that he would like to change the ceiling design, preferring a more classical ceiling design with wood panels curved in the long section and straight in short section, a solution used in many concert halls, for example in the *Lingotto Hall* in Turin and the medium-sized concert hall in *Parco della Musica* in Rome, both designed by Renzo Piano. We were originally opposed to this design change, fearing a reduction in both lateral energy and early reflection coverage. Some simple modifications to the parametric model allowed the new ceiling to be modelled quickly and analysis of the results showed that the new proposed design could be made to work, and lead to at least equivalent if not better acoustic results. Given the rather small dimensions of the hall, the radius of curvature of the ceiling panels was reduced, and the balcony fronts of the technical balcony were curved as well as vertically inclined. Further studies were performed on the balcony front inclination angle and the addition of curvature to better distribute early reflections. Finally, a variable height stage reflector was added for improved versatility. The results indicated that lateral reflections for the rear part of the audience would be created by curved and angled balcony fronts of the technical balcony as well as by the corner between the side walls and the ceiling.

2.3 Final Auditorium Design

The final architectural design incorporated the results of the acoustical studies. The following figures show the architectural longitudinal section and plan of the auditorium. Subsequently, a view of the final computer model and photos of the actual interior of the hall are shown in similar configurations.

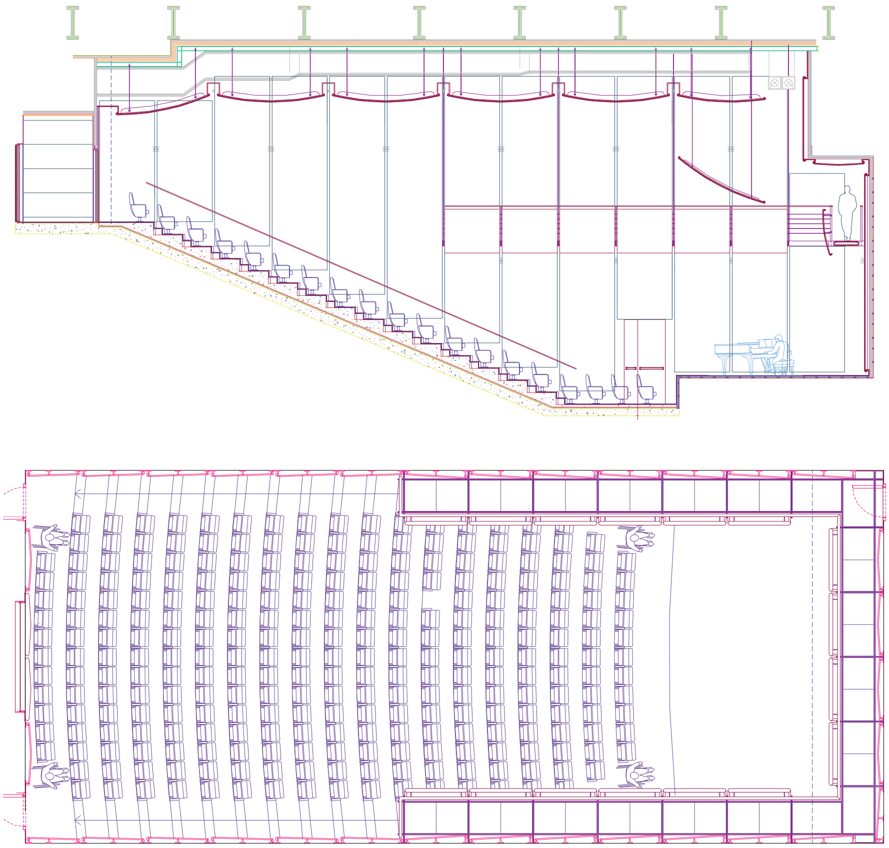

__Figure 5:__ (Upper) Longitudinal Section of the Auditorium, showing the rather steeply raked seating plane, the curved ceiling panels, and the curved and inclined balcony fronts.(Lower) Plan (at rear parterre and technical balcony level) of the Auditorium, showing the extent of the technical balcony, and the angled and V-shaped wall panels (in red).

2.4 Vibration isolation

Acoustic testing during the design period confirmed that subway vibration was present in the bedrock, from one the major New York subway lines at a distance of about 100 m. At the same time, it had to be avoided that acoustic vibration solutions would further reduce the already limited width of the Auditorium. Acoustic vibration isolation was integrated into the design using a floating concrete slab and resiliently connected finishes, *i.e.* without a secondary massive structure. The side wall finish complex, consisting of the wood panels and a triple layer dry wall, is supported on the floating concrete slab, with resilient lateral restraints, and the ceiling complex is hung from vibration isolators. The vibration isolation was successful, no subway noise can be perceived in the Auditorium, without any significant increase in the thickness of the construction buildup.

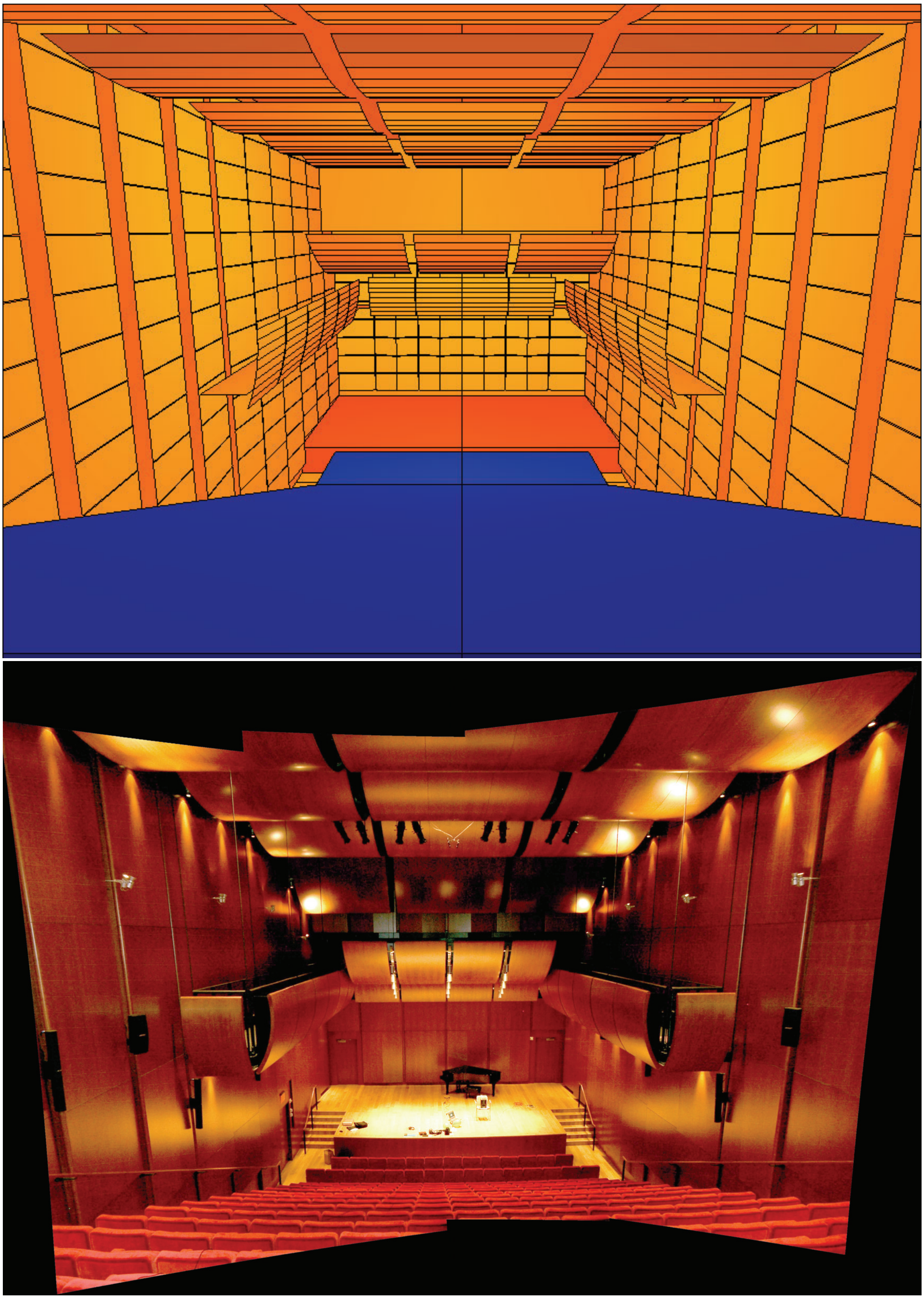

Figure 6: *(Upper)View of final computer mode. (Lower) Interior photo of the completed auditorium.*

Figure 7: *(Left) View of the hall and the ceiling from the stage. (Right) Detail of the technical balcony edge, showing the curved and inclined balcony fronts.*

3 EVALUATION

3.1 Opening and listening evaluation

The Morgan Auditorium, now called Gilbert Lehman Hall, opened in April 2006 with a concert by Thomas Hampson, Craig Rutenberg, and the Vermeer Quartet. It has since been used extensively for concerts as well as presentations and lectures. The most stunning aspect of the acoustics of the Morgan Auditorium certainly is the presence of the sources, directly linked to the size and width of the room. The hall therefore is perfectly adapted to chamber music and especially historic instruments, and corresponding concert series have been highly successful. Nevertheless, the room can handle loud musical sources without saturating, probably due to the non-parallel surfaces and the sufficient amount of acoustic diffusion through curved and/or non-parallel surfaces. The other stunning aspect of the acoustics of the room is speech intelligibility, linked to the moderate reverberation time, the small size of the room, high clarity and strong envelopment. Conversations on stage, even when held at normal or low speech levels, and even when the speakers are not facing the audience, are easily and clearly understood in all seats in the audience area.

3.2 Measurements

In November 2006, a series of measurements and recordings were made in the completed hall. This section provides a comparison of some of the measurements with the acoustic computer model simulation made during the design phase of the project. Measurements were made using a Genelec 1030A loudspeaker, at 1 m height facing the audience seating, and a Neumann U87 variable directivity microphone. While this loudspeaker is not omni-directional, as stipulated in measurement standard ISO 3382[1], other equipment was unavailable at the time. Computer simulations were made using an omni-directional source. Simulation and measurement positions were according to the configuration in the following figure. Actual measurement positions correspond to positions 00,02,04,06,08 while numerical were carried for all positions shown. Source position is the position noted *A0*.

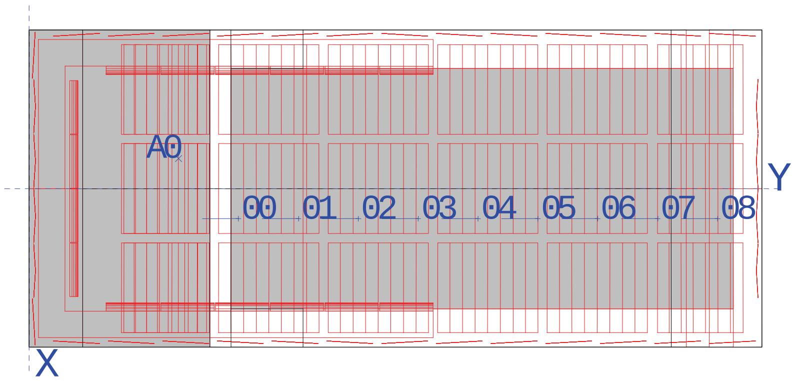

Figure 8: *Measurement position reference.*

Results of the mean reverberation times (T-15) and early decay times (EDT-10) over all positions in octave bands for the measured positions are shown, in addition to the results for the acoustic model, in the following figure. Reverberation time results show a very high correspondence, while the numerical model appears to under predict the early decay time.

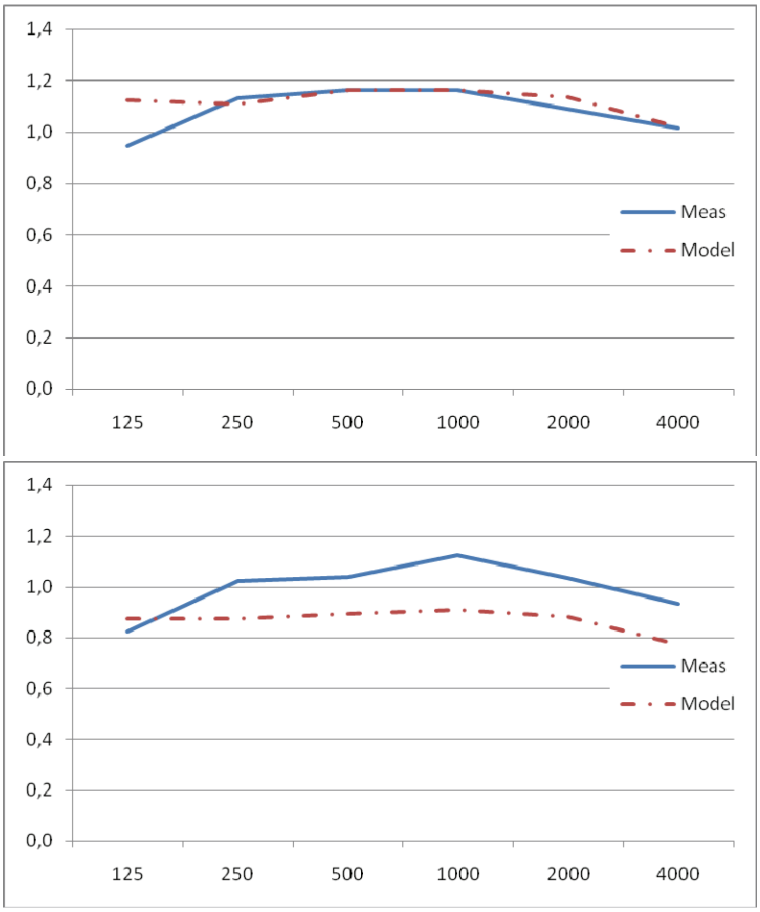

Figure 9: *(Upper) Mean reverberation time, T-15. (Lower) Mean early decay time, EDT-10.*

Another important measure for the quality of the hall is the level of clarity and early lateral energy. A comparison of the mean clarity over measurement positions, and frequency bands 500, 1000, 2000 Hz, termed $C_{80}(3)$, shows 4.6 dB and 5.1 dB for the measurement and model respectively.[2] Further details are provided in the following figure, which show that while the average value agreement and that of the center positions of the hall are quite respectable, there are noticeable variations. Comparison of early lateral energy fractions, LFC, averaged over the measurement positions and octave bands 125, 250, 500, 1000 Hz, noted LFC_{E4}, shows 25% and 26% for the measurement and model respectively.[1,2] A more detailed analysis is shown in the following figure for the different measurement positions. The correspondence is quite good, and both sets appear to follow similar trends.

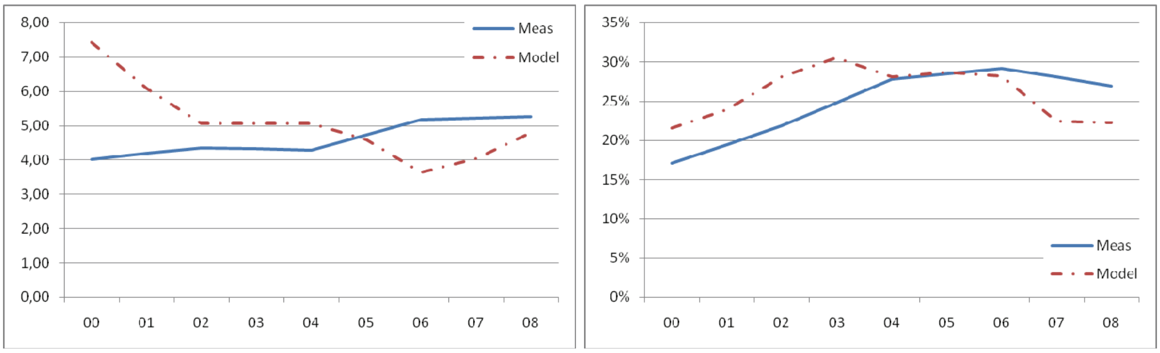

Figure 10: *(Left) Clarity, C_{80}(3). (Right) Early lateral energy fraction, LFC_{E4}.*

4 CONCLUSION

The design goals of The Morgan Library & Museum auditorium were to create a "jewel" performance space for acoustical music within a severely restricted footprint. In working with the architect, and through the use of a highly flexible parametric room model, we were able to optimize the acoustics of the hall through the use of a large number of wall and ceiling panels. The configuration of these architectural elements was optimized in the numerical model. Variations were made to the geometrical configuration and these trends were analyzed in discussions with architect in order to achieve the best acoustical and aesthetic results.

Post-opening measurements have been made of the quality hall investigating several key parameters at various positions using a typical loudspeaker. These measurements have been compared to the original design phase numerical simulations using an omni-directional source. Reverberation time, T-15, and global parameter averages for clarity, C_{80}(3), and early lateral energy, LFC_{E4}, are in generally in good agreement. Some variations though are found when examining specific locations. Results for the early decay time, EDT-10, showed that the model under-predicted the results more than would be expected.

While it is not expected that there be perfect agreement between the design phase model and the final constructed hall, it is encouraging to see that for some parameters there is very high agreement, especially for such a complicated room containing a large number internal panels of varying curvature.

5 REFERENCES

1. ISO 3382:2000 Acoustics—Measurement of the reverberation time of rooms with reference to other acoustical parameters (2000).

2. L. Beranek, Concert and Opera Halls : How They Sound, Acoustical Society of America, (1996).