THE ACOUSTIC OF THE STORE SAL, OSLO OPERA HOUSE

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1 INTRODUCTION

As part of the commissioning of the new opera house in Oslo, BrekkeStrandArup (a joint venture between Brekke Strand Akustikk and Arup Acoustics) carried out extensive acoustical testing of the main auditorium (Store Sal). Impulse responses were measured throughout the auditorium in different configurations and subjective assessments were carried out during rehearsals and a test performance. This paper provides an overview of the measurements that have been made and compares the results with the design targets derived in response to the brief for the building.

2 DESIGN TARGETS

The authors of this paper have previously described the detailed acoustic design (including the geometry and room finishes) of the Store Sal[1]. The overall performance requirement for the Store Sal as identified in the project brief was that "the main auditorium must have excellent acoustics for traditional proscenium-type grand opera"*.* In response to this, a set of objective design targets were generated relating to the subjective aspects of reverberance, clarity and loudness. These objective design targets for the occupied auditorium are also presented in this reference[1].

3 UNOCCUPIED MEASUREMENTS

3.1 Measurement Set-Up

For the unoccupied measurements, the stage was dressed with a 'standard' set of cloths, including 4 sets of borders, a full height back cloth and significant hangings at high level in the flytower. Some sound reflecting elements of a set (for a Den Norske Opera (DNO) production of Rigoletto) were placed upstage. The mid frequency reverberation time in the flytower (with the fire curtain lowered) was 1.8s rising to 2.3s in the 125Hz octave band. This represents an 'average to lightly damped' stage condition that was considered typical for a production by DNO. There were around 60 seats in the orchestra pit.

An omni-directional loudspeaker was placed at 5 source locations on the stage and 2 in the pit, chosen to represent typical singer and orchestra positions. Room impulse responses were measured at seated ear height at up to 23 measurement positions in the Store Sal for each source position. A pink noise signal was played through the amplifier and omnidirectional loudspeaker (generating a reference sound power level) to derive the strength values. Values for performer support were derived from impulse response measurements 1m from the source position.

3.2 Reverberation Time (RT) and the Effect of the Variable Absorption

$T_{30(500\text{-}1k)}$ averaged over all source and receiver positions in the unoccupied Store Sal was 2.15s with the fire shutter between the auditorium and the flytower raised. When the fire shutter was lowered, $T_{30(500\text{-}1k)}$ increased by 0.1s. The design target was $T_{30(500\text{-}1k)} \geq 1.7$s. Figure 1 shows the effect on RT of extending the variable absorption in the Store Sal with the fire shutter both raised and lowered.

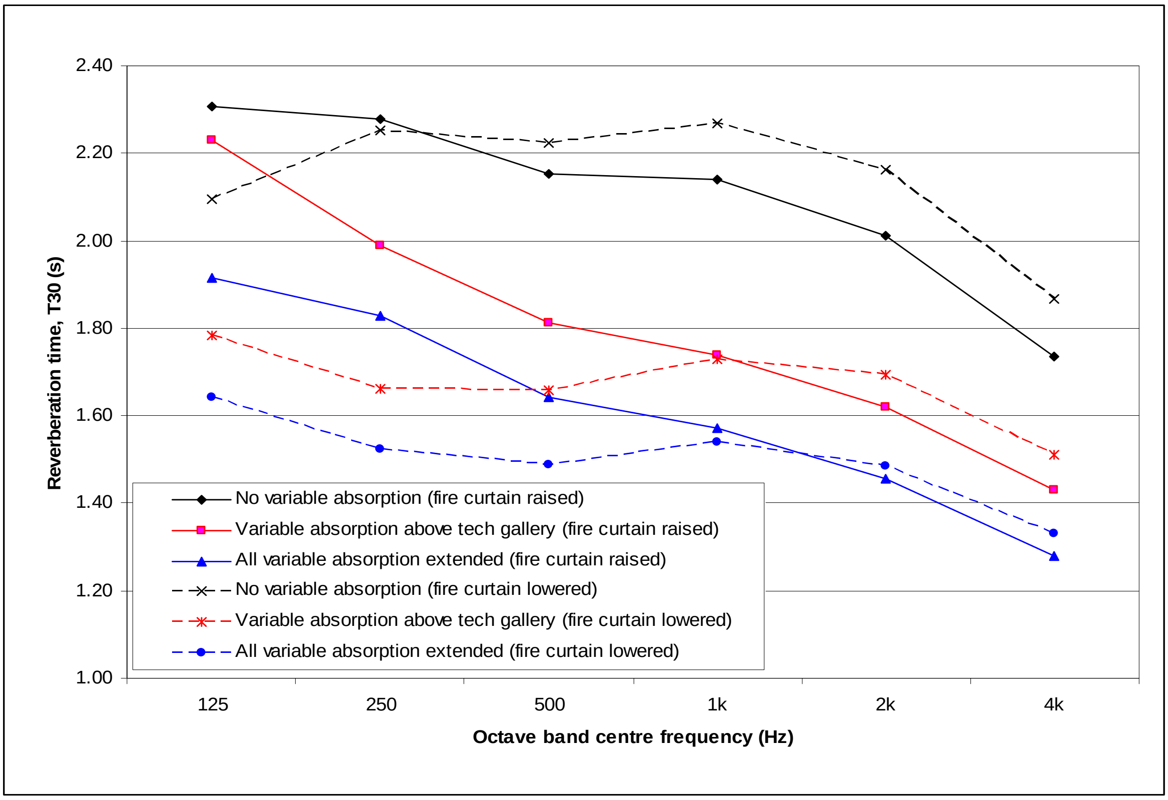

Figure 1 The effect of variable absorption on unoccupied reverberation time with the fire curtain lowered (pit source positions only) and raised (pit and stage source positions)

These results show that the variable absorption is effective at reducing T_{30} across the frequency range, particularly the curtains that can be extended at high level above the technical gallery. These upper curtains not only add sound absorption into the space but also help to reduce the acoustic room volume by closing off the 'ears' at high level.

The effect of the coupled flytower volume as a net absorber at higher frequencies and contributor to reverberance at low frequencies is apparent from comparison of the solid and dotted lines of similar colour in Figure 1. With the fire shutter lowered the low frequency reverberation in the Store Sal is also well controlled in the presence of the variable absorption.

3.3 Early Decay Time (EDT)

The average value (all stage and pit sources) for $EDT_{(500\text{-}1k)}$ in the unoccupied Store Sal was 1.9s. The ratios of mid-frequency EDT to RT for each measurement position averaged over stage and pit source positions (with the fired shutter raised) are shown in Figure 2. As desired, the ratio of EDT to RT for the stage sources is generally lower than that for the pit. The design target was 85% ≤ EDT ≤ 95% of T_{30} for the stage and 85% ≤ EDT ≤ 100% of T_{30} for the pit.

For the stage sources there is greater variation of the EDT and hence of the EDT to RT ratio (the RT measurements were similar throughout the Store Sal exhibiting a standard deviation from the mean of around 0.05 at mid-frequencies over 137 measurements). Positions under the balcony overhangs have EDT to RT ratios lower than the design target. Some positions in the side balconies, particularly in the 3rd balcony, have EDT to RT ratios longer than the design target.

With the exception of the measurement position very close to the orchestra pit, the EDT to RT ratios for the orchestra pit sources generally meet the design target. It is noteworthy that the ratios remain high underneath the balconies.

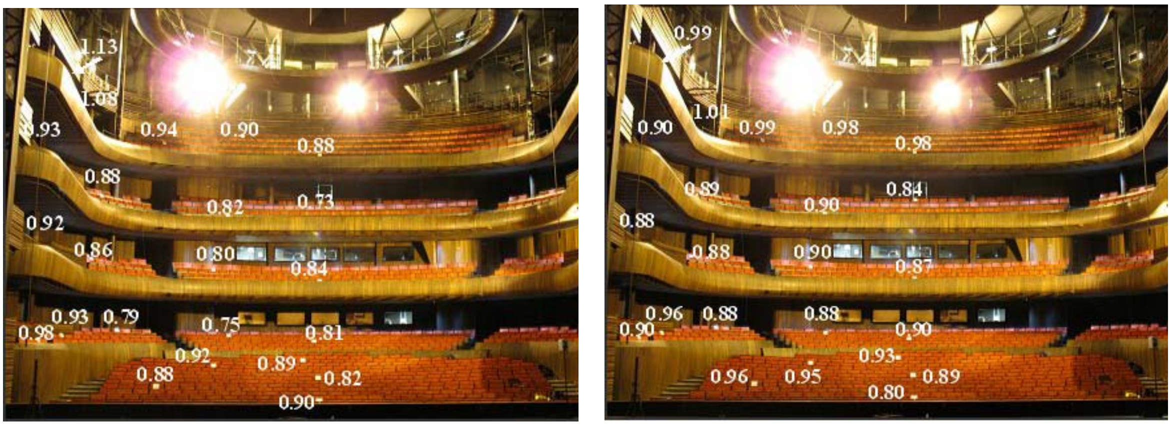

Figure 2 Ratio of EDT to RT for stage (on the left) and pit (on the right) sources

It is an interesting feature of the Store Sal acoustic that the EDT in the third balcony is longer than elsewhere in the auditorium. This is clearly shown in Figure 3 and is symptomatic of the geometry at high level in the auditorium. Measurements with the variable absorption extended at high level above the technical gallery reduced the EDT in the 3rd balcony from 2.1s to 1.7s.

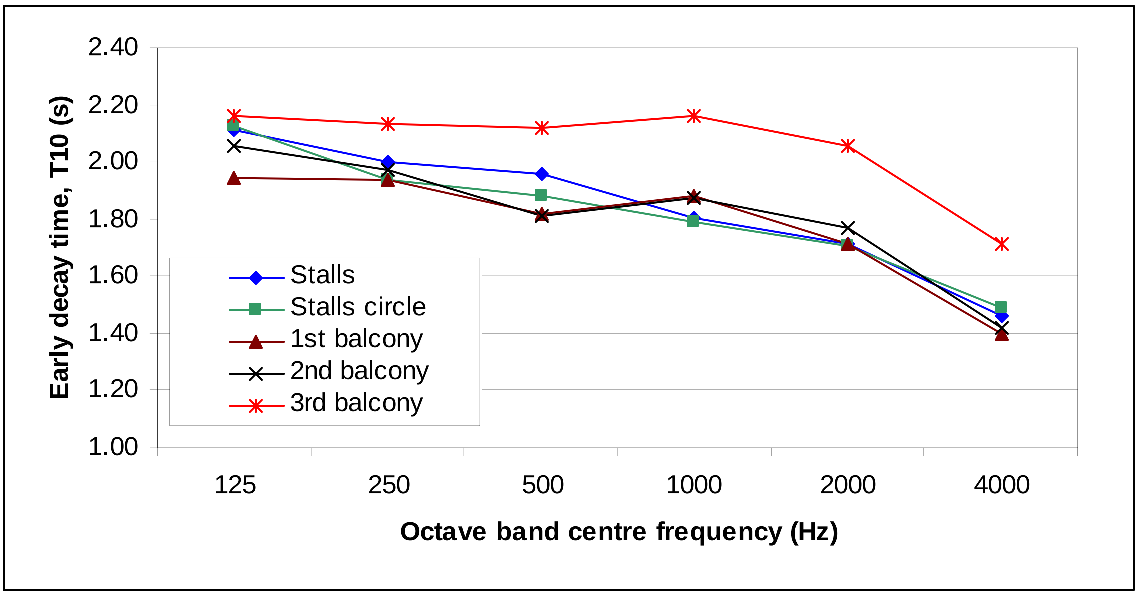

Figure 3 Early decay time averaged over seating area

3.4 Clarity

The measured values for $D_{50(500\text{-}2k)}$ and $C_{80(500\text{-}2k)}$ in the unoccupied Store Sal are shown in Figure 4. It should be noted that these were all made with an omnidirectional loudspeaker and as such the $D_{50(500\text{-}2k)}$ will underestimate the actual vocal clarity from the stage.

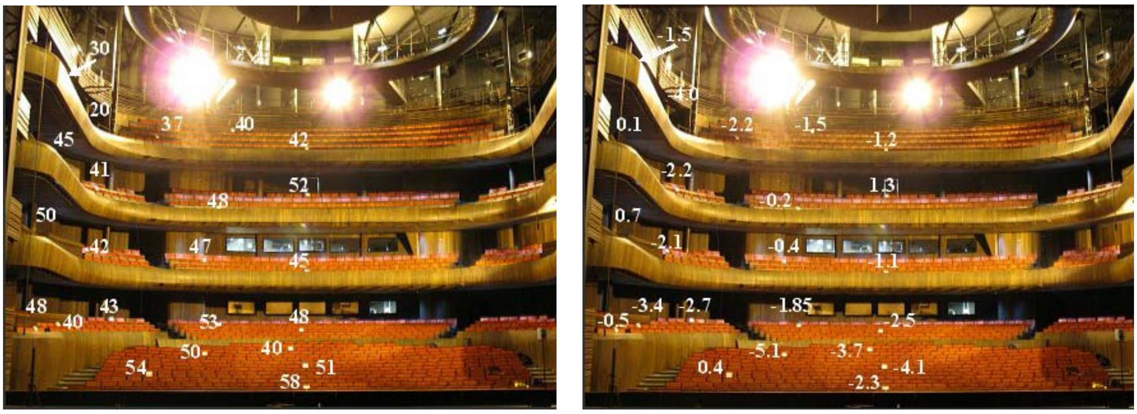

Figure 4 Left: $D_{50(500\text{-}2k)}$ (%) averaged over stage sources, and right: $C_{80(500\text{-}2k)}$ (dB) averaged over pit sources

3.4.1 Vocal Clarity (D_{50})

The spatial average $D_{50(500\text{-}2k)}$ from the stage source positions (with an omnidirectional source) was 45%. The design target was $D_{50(500\text{-}2k)} \geq 45\%$. Although measurements with a directional loudspeaker source were not carried out in Store Sal, (unpublished) measurements at Copenhagen Opera House by Arup Acoustics suggest that an increase in D_{50} of around 15 percentage points may be expected between an omnidirectional source and a loudspeaker source with similar directivity to a singer. Based upon this assumption, the vocal clarity meets the design target. It is interesting to note from more detailed analysis that average D_{50} values in the 3rd balcony increased as the (omnidirectional) source position was moved upstage.

3.4.2 Orchestral Clarity (C_{80})

The average $C_{80(500\text{-}2k)}$ from the orchestra pit source positions was -1.8dB, compared with the design target of $-4\text{dB} \leq C_{80} \leq 0\text{dB}$. C_{80} is lowest in the stalls (where there is no direct sound path between the orchestra pit sources and the receiver locations) and in the 3rd balcony. These values are in keeping with a more reverberant orchestral sound that will support the orchestral sound for grand opera works. With the exception of just 2 measurement locations, the measured values in the unoccupied auditorium met the design targets for the occupied room. It is expected that the orchestral clarity will increase with occupancy.

3.5 Strength (G)

The spatial average G_{stage} from the stage positions was 1.0dB and from the orchestra pit positions was 1.9dB. The range of G_{stage} measured across the unoccupied Store Sal was -1.3dB to 2.9dB. This is a pleasingly low spread for an opera house. From previous measurement experience it is expected that G_{stage} increases by around 1.5dB with a directional source.

With the exception of the measurement location closest to the orchestra pit and locations in the side balconies, G_{stage}-G_{pit} is between -1.5dB and +0.4dB. Once these figures have been corrected to account for a +1.5dB increase in loudness attributed to the directionality of singers (and it is assumed that the presence of audience will similarly affect both stage and pit sources), the average ratio of G_{stage}-G_{pit} 0.4dB. This is a less than the design target but, with good set design to help support the stage sound, should allow the conductor to satisfactorily balance the loudness of the stage and pit sounds.

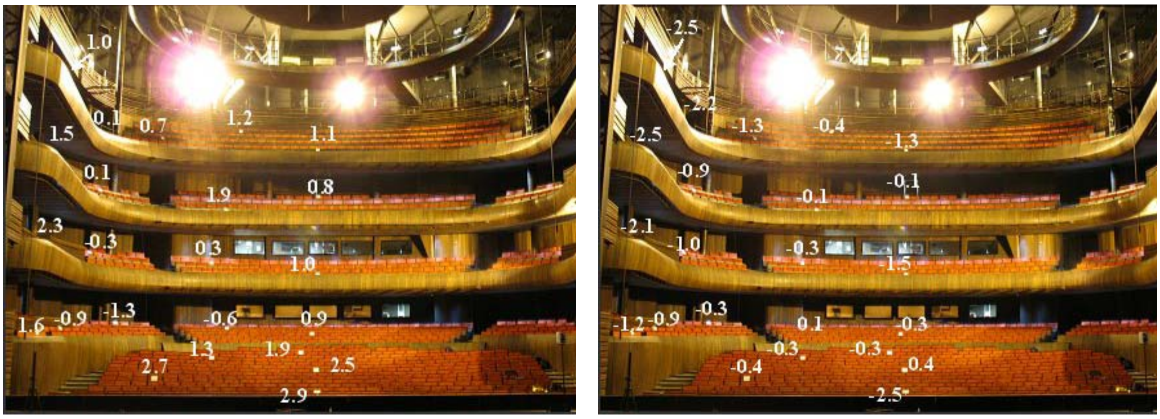

Figure 5 Left: strength averaged over stage positions (G_{stage}), right: uncorrected strength balance (G_{stage}-G_{pit}) at each measurement position

3.6 Performer Support

Performer support was measured at 4 positions on stage and 2 in the pit.

On stage, at locations distant from the sound reflecting stage set elements, mid frequency ST_{Early} values of -21.6dB to -23.3dB were measured. At the positions closest to the reflecting set elements, ST_{Early} was -16.7dB. This suggests that a variation of ST_{Early} of 7 or 8dB can be expected on stage dependent on the singer's proximity to sound reflecting elements, but that a typical worst case (with no reflections from local set elements) would be -24dB. For the 2 orchestra pit sources, values of -13.4dB and -11.4dB were measured. These are relatively high results for orchestral support in an orchestra pit.

The mid-frequency ST_{Late} on stage ranged from -17.6dB to -20.3dB, showing less variation with proximity to sound-reflecting set elements, as expected. For the 2 orchestra pit sources, values of -18.3dB and -18.5dB were measured. The corresponding values of ST_{Tot} were between -14.1dB and -18.6dB for the stage sources and -10.7dB and -12.2dB for the pit sources.

4 MEASUREMENTS WITH THE ORCHESTRA SHELL IN PLACE

Measurements were made in the unoccupied Store Sal with the orchestra shell in place, surrounding the orchestra risers and choir seating.

4.1 Reverberation Time and EDT

Figure 6 shows the change in RT due to the presence of the orchestra shell. The comparison shows the low frequency RT to be shorter with the shell in place. This is probably a function of the low frequency absorption by the (relatively lightweight) orchestra shell and the reduced effect of the flytower sound decay.

The EDT measured with the orchestra shell exhibits similar spatial characteristics, albeit more pronounced over a wider frequency range, to that described in Section 3.3.

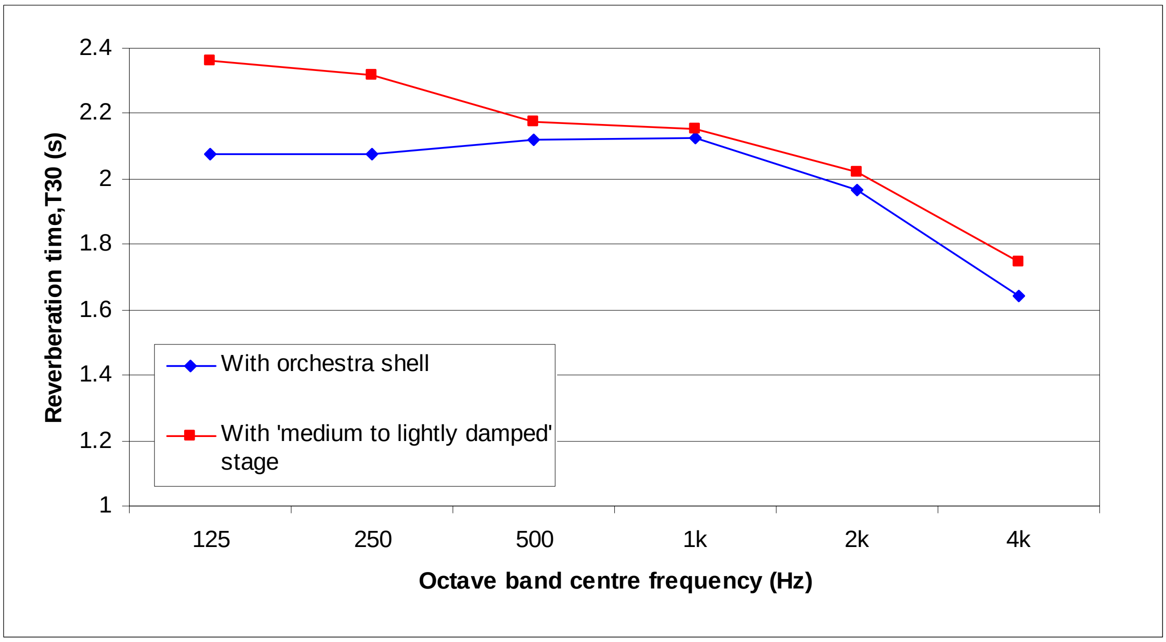

Figure 6 Unoccupied reverberation times (from stage sources only) with and without orchestra shell

4.2 Clarity and Strength

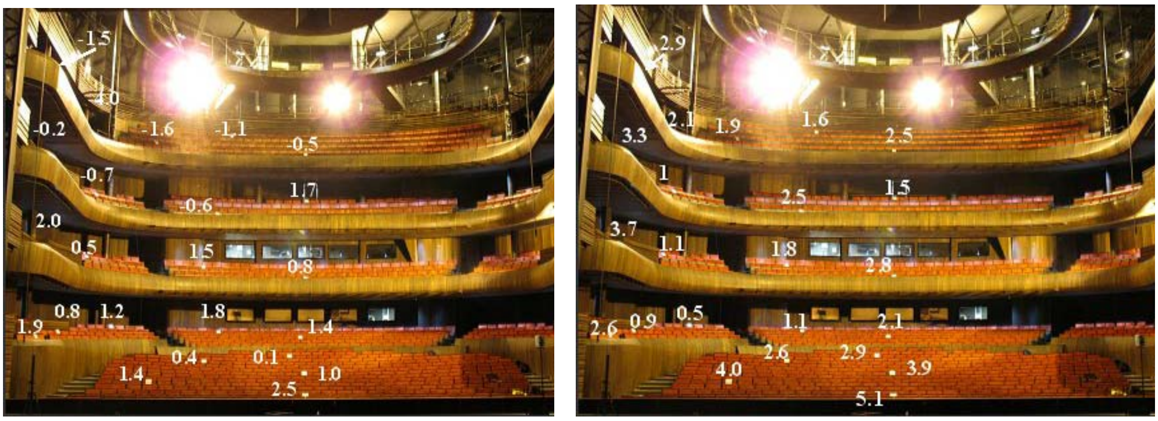

Figure 7 Measurements with the orchestra shell in place, left: C_{80}, right: G

The measured orchestral clarity from the stage sources with the orchestra shell is shown on the left in Figure 7. As expected, with the orchestra shell on stage, the orchestral clarity is greater in the lower levels of the Store Sal than when the orchestra is in the pit. C_{80} values in the upper levels (where a direct line of sight exists into the orchestra pit) are very similar whether the orchestra is in the pit or on stage.

The G results with the orchestra shell are shown on the right in Figure 7. These results show a very even loudness across the Store Sal, with a range of 0.5dB - 5dB. Comparison with the G results from the stage with no shell and the orchestra pit in Figure 5 shows an increase of between 0.4dB and 2.2dB (average 1.4dB) at each measurement location, supporting the acoustical benefit of the presence of sound reflecting surfaces on the stage.

4.3 Performer Support

Performer support was measured at 6 positions across the orchestra playing area.

The measured mid-frequency ST_{Early} ranged from -12.6dB to -17.3dB, the lowest value being in the woodwind section, most distant from the orchestra shell surfaces. This suggests that a variation of ST_{Early} of ~ 5dB can be expected across the orchestra. It is interesting to note that ST_{Early} with the orchestra shell is similar, or even a little lower than that measured in the orchestra pit in traditional opera format. The mid-frequency ST_{Late} measured in the orchestra playing area ranged from -16.5dB to -18.3dB, which is very similar to that measured in the orchestra pit. The corresponding range in ST_{Tot} was -11.5dB and -14.7dB, again showing very similar values to those measured in the orchestra pit.

5 OCCUPIED MEASUREMENTS

5.1 Measurement Set-Up

For the test performance (occupied test) the stage was 'lightly dressed' with a 'standard' set of cloths, including 4 sets of borders, a full height back cloth and hangings at high level.

Impulse response and G measurements were made at 8 source-receiver combinations in the occupied Store Sal. There were 2 receiver locations (one in the mid-rear stalls and the other towards the centre of the 3rd balcony) for each of 4 source positions (2 in the pit and 2 on stage). Measurements were also made in the flytower with the fire curtain lowered.

5.2 Results

The T_{30} results are shown in Figure 8. Comparison of the flytower T_{30}s shows a significant difference in the stage conditions for the unoccupied and occupied tests. $T_{30(500\text{-}1k)}$ in the occupied Store Sal was just > 2.1s, similar to that in the unoccupied condition. This is shown by the blue solid line in Figure 8. For a given stage condition, it is expected that the T_{30} will be shorter in an auditorium when it is occupied. The reason for this not being the case in the Store Sal is the effect of the flytower. The dominance of the sound decay from the flytower (blue dashed line in Figure 8) on the occupied T_{30} can be clearly seen, as the Store Sal T_{30} at mid and high frequency is very similar to that measured in the flytower alone. This is in contrast to the unoccupied measurements, (shown in red in Figure 8) where the flytower T_{30} was significantly shorter than the overall T_{30}.

The occupied test results for the design parameters relating to EDT/RT ratio, clarity and loudness at the 2 measurement locations (each averaged over 4 source positions) are shown in Table 1. All of the occupied measurement results were affected by the lightly damped condition of the flytower. As such, they represent a useful data point in describing the "highest reverberance, lowest clarity" condition for the occupied Store Sal. Although direct comparison with the design targets is rather inappropriate (as the design targets apply to 'typical' opera production conditions with a significantly more damped flytower) they are included in Table 2 for completeness.

The loudness measurements show a much greater reduction for the stage sources between unoccupied and occupied tests than the pit. It is considered that this is a result of the complete lack of sound reflecting elements around the stage during the occupied tests, and perhaps highlights the importance of set design in augmenting the loudness of the singers.

In summary, the design of the Store Sal has resulted in a room acoustic that provides good vocal and orchestral clarity in line with the design targets together with a $T_{30(500\text{-}1k)}$ that may be regarded as numerically satisfactory for symphonic performances.

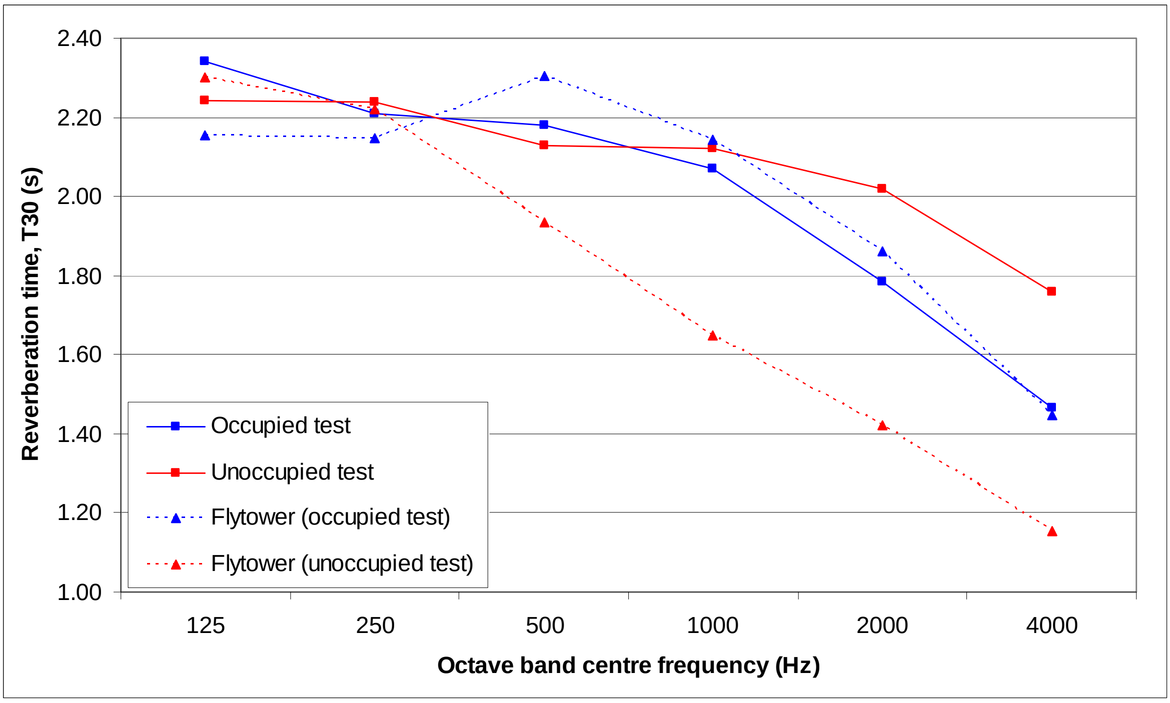

Figure 8 Reverberation times measured at the time of the unoccupied and occupied acoustic tests

Parameter	Rear stalls position	3rd balcony position	Design target
Mid frequency T_{30} (s)	2.11 (2.10)	2.13 (2.15)	>1.7
EDT/RT stage sources	0.81 (0.87)	0.84 (0.91)	0.85 – 0.95
EDT/RT pit sources	0.81 (0.93)	0.89 (0.98)	0.85 – 1.0
D_{50} stage sources (%)*	48 (52)	53 (50)	≥45
C_{80} pit sources (dB)	-3.6 (-4.1)	-0.4 (-1.5)	$-4dB \leq C_{80} \leq 0dB$
G_{stage} (dB) allowing +1.5dB for stage directivity	0.5 (3.3)	-0.7 (2.5)	≥0
G_{pit} (dB)	1.8 (2.2)	0.8 (1.6)	≥ -2
G_{stage}-G_{pit} (dB)	-1.3 (1.1)	-1.1 (0.9)	≥ 2

Table 1 Occupied results (unoccupied equivalent in brackets, with significantly different flytower condition)

* 10 percentage points added to the values, which were measured with an omnidirectional source, to correct for voice directivity and hence enable reasonable comparison with the acoustic design targets

6 REFERENCES

1. Newton J & Harris R, The acoustic design of Oslo Opera House, 2007 Proc. Int. Symp. on Room Acoustics, part of the 19th Symp. ICA, Seville.