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Tent-shaped concert halls, existing and future

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I. INTRODUCTION

The success of the Tokyo Opera City Concert Hall[1] indicates that the advantages of the shoebox geometry can be equaled or possibly surpassed in halls with inverted-V cross-section ceilings. Not referenced in the Tokyo Hall paper is the earlier success of The Maltings Concert Hall in Snape, England, nor many North American worship spaces with inverted-V ceilings or entire cross sections that have good reputations for concert hall acoustics, nor the more recent halls for which McKay Conant Brook were consultants. However, from the design of Symphony Hall Boston through such recent halls as Benaroya Hall in Seattle,[2–4] the rectangular shoe box has been considered by many architectural acoustical designers and consultants as an ideal form. The success of concert halls in the round with "vineyards" and/or electroacoustics has not challenged the shoebox's supremacy, but possibly the tent shape will.

Reference 1, concerning the Tokyo hall, shows that reverberation time calculations can be predicted with accuracy in inverted-V designs as well as in rectangular cross-section designs. Beyond concert hall design, the tradition of the rectangular shoebox hall is paralleled by the tradition of North American worship spaces with inverted-V ceilings that have excellent concert hall acoustics, such as the Church of the Advent, Boston,[2] The Bryn Mawr Presbyterian Church, Bryn Mawr, PA, Trinity College Chapel, Hartford, CT, and some with no vertical sidewall surfaces, such as the Air Force Academy Chapel, Colorado Springs, Congregation Beth El, Bloomfield Hills, MI, and the First Presbyterian Church, Stamford, CT, the "Fish Church."[5] The potential advantages of the inverted V as a cross section can include the following: (1) provision of lateral diffusion from smooth surfaces without the need of surface roughness, but only if the apex angle is less than 90°; (2) savings in construction costs, but only if the building or the inverted-V portion of the building is not exceptionally narrow; (3) possibilities for remodeling to increase room volume for increased reverberation time with continuous use of the building during the remodeling. The restraints on the first and second appear contradictory, but there is a range of apex angles where both advantages apply.[9]

In rereading the first reference, I was reminded of a telephone conversation of some 25 years ago. The architect, Yamasaki, called and said: "David, they are opening Beth El with a concert by the Detroit Symphony. I told them the building was designed as a synagogue and not a concert hall, but they are going ahead anyway." I took the number of seconds to mentally review the design, and then replied: "Don't worry, it will be all right. Just be sure to cover the carpet on the Bimah (the front platform) with plywood, especially under the 'cellos and double-bases." And they did so, and the concert was a success, and the acoustics were judged favorably. Refer to Fig. 1, which includes a Congregation Beth El, Bloomfield Hills, Michigan, photograph. The use of reflected light in a small model contributed to the design, and Gerald Marshall worked with me.

However, there is an even earlier worship space demonstrating good concert hall acoustics, the First Presbyterian Church of Stanford, Connecticut, the famous Wallace Harrison "Fish Church."[5] This church's acoustics were changed, unfortunately, by an attempt to correct a noise-produced intelligibility problem by massive sound-absorbing treatment and an underpew sound system without line of sight from the loudspeaker to ear. This situation and the use of an electronic instead of pipe organ prevented the church from serving as a model for good concert hall acoustical design. The installation of a fine Visser–Rowland pipe organ and the restoration of the original acoustics, done under the direction of the music minister, should restore it to that role (Figs. 1 and 2).

II. LATERAL DIFFUSION

The reflections from smooth vertical parallel walls and a flat ceiling are specular and not diffuse, but an inverted-V ceiling with an apex angle less than 90° allows a significant fraction of the energy to be reflected twice off the ceiling before returning to the sound-absorbing audience, and the angles involved can be very different for the double-reflected energy, as compared with the single reflections. This may possibly provide a sense of envelopment and, while not

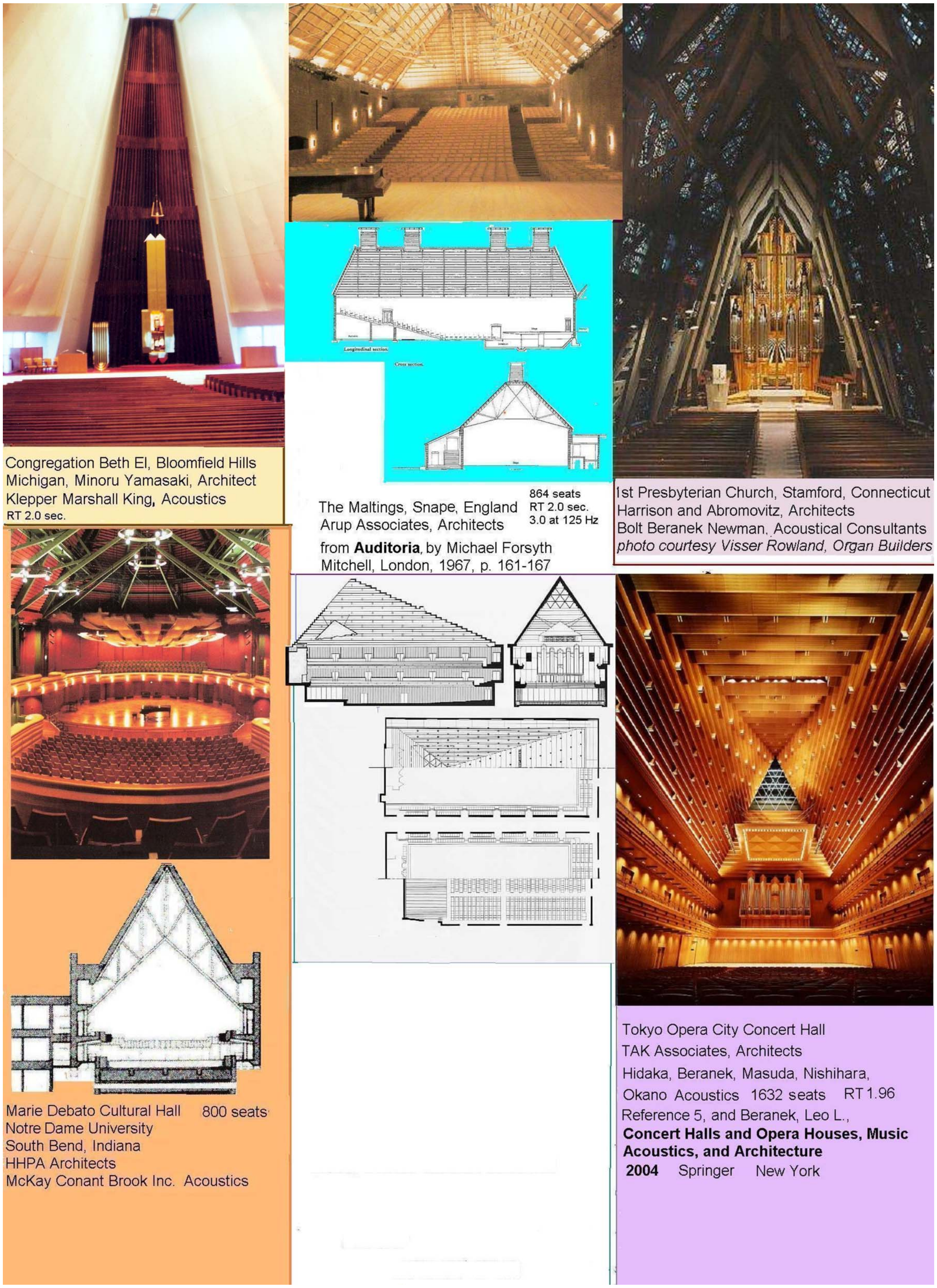

FIG. 1. (Color online) Three concert halls with apex angles at or close to optimum and two worship spaces used as concert halls on occasion.

100% nonspecular, is certainly no longer 100% specular. Figure 3provides a comparison. Very small apex angles can allow multiple ceiling reflections but can also increase construction costs instead of decreasing them.[9]

III. CONSTRUCTION COSTS

Assuming equal interior volume (and end wall areas), a pure inverted-V hall will have twice the height of the comparable rectangular hall, resulting in the same average ceiling

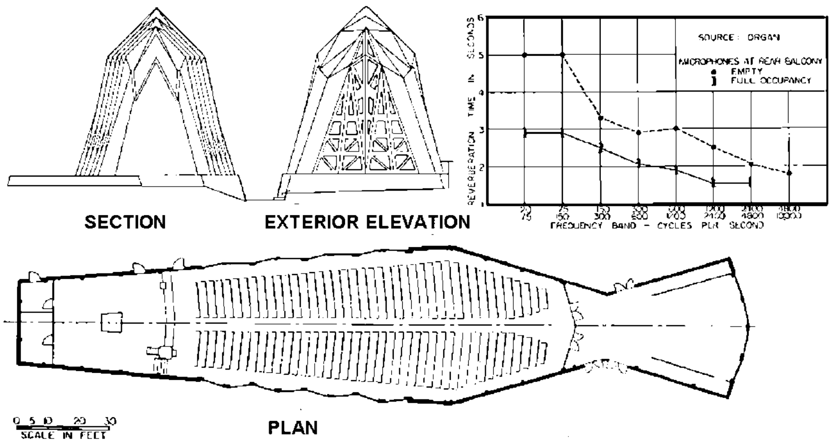

FIG. 2. Design and RT characteristics of the first Presbyterian Church, Stamford, CT (Ref. 5).

height (see Fig. 4). A comparison of the total sidewall and ceiling area of construction and linear length of transverse and vertical steel beams and columns or other frame members may be derived from geometry to be given by the equation:

$$R = 2(4 + r^2/4)^{1/2}/(2 + r) = (16 + r^2)^{1/2}/(2 + r), \qquad (1)$$

where r is the width of the hall divided by the height of the rectangular hall, which is average height of the inverted-V hall, and R is the ratio of side and top surface area, which is the inverted-V hall divided by the rectangular hall that is also equal to the ratio of linear distances of side and top framing across the hall.

However, the depth of the steel web required is dependent on the length of the span. As a first approximation, the depth can be considered proportional to the length of the span.[9] This comparison is given by the equation

$$S,\ \text{structural depth ratio,} = 2(4 + r^2/4)^{1/2}/2r = (16 + r^2)^{1/2}/2r. \qquad (2)$$

Some measure of the total savings in using an inverted V can be obtained by multiplying the results of the two equations. The following table results:

Apex angle	r (width/ average height)	R (V area/ rectangular area)	S (V structure depth/ rectangular structure depth)	RS[10]
180	Inf.	1.00	0.50 (simplification not valid)	0.50
134	10	0.90	0.54	0.47
127	8	0.89	0.56	0.49
113	6	0.90	0.60	0.54
103	5	0.91	0.64	0.58
90	4	0.94	0.71	0.67
73	3	1.00	0.83	0.83
54	2	1.10	1.11	1.22
28	1	1.35	2.24	3.59
Zero	1/Inf.	2.00	Inf. (simplification not valid)	Inf.

Clearly, some recent concert halls have angles that provide both some lateral diffusion and some savings in construction costs, by employing conventional rectangular construction up to a specific height and then transitioning to an inverted V (see Fig. 1and Ref. 4). All credit to their designers.

IV. RENOVATION DURING USEFUL OCCUPANCY

The concept of an inverted-V roof for a concert hall suggests the possibility of remodeling such halls as London's

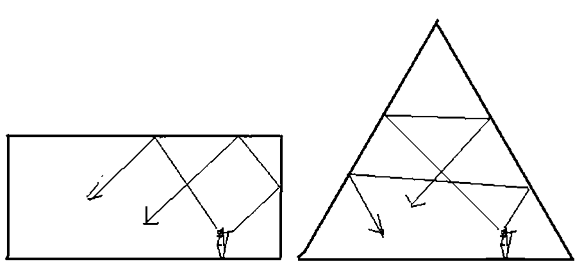

FIG. 3. Lateral section, how the use of an inverted-V ceiling can add lateral diffusion.

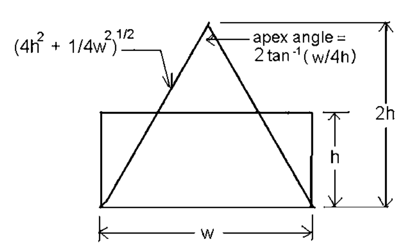

FIG. 4. Height, width, and angle relationships, V ceiling vs rectangular hall.

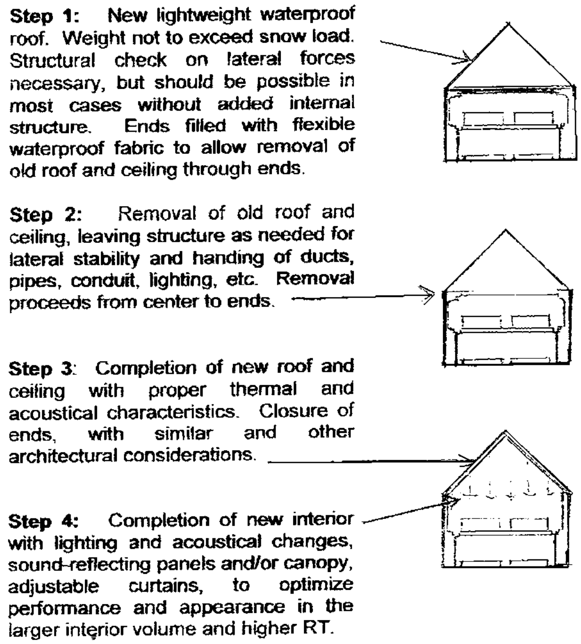

FIG. 5. Use of an inverted-V ceiling for adding volume to a hall for increased RT, lateral section shown.

Royal Festival Hall to have increased volume for increased reverberation time while continuing to use them. Possibly, sidewalls may need some additional structural strength. An initial inverted-V roof within the snow-load or rain-load tolerances of the building is constructed while leaving the original flat roof in place. When the inverted-V roof construction has progressed to the point where the building is weather tight, the flat roof can be removed section by section, opening up the added volume formed by the inverted V. The weight can then be added to the new roof, and the other required acoustical and architectural adjustments can be made to the interior (see Fig. 5).

V. FURTHER WORK

I am hopeful that the future will bring to completion enough halls with the inverted-V cross section to enable objective measurements to show what, if any, differences are there in such measurement tests of concert hall characteristics, including spatial information, variability of levels and directional pattern of received energy at various listening position, early-to-reverberant ratios as a function of frequency, lateral energy fraction as a function of frequency, and directional diffusion, when comparing similar halls in seating capacity and area, cubic volume, reverberation times, and seating and floor plans, differing only in the use of a rectangular cross section on the one hand and an inverted-V cross section on the other.[6] It may be quite a few years before such objective data are available! Until then, the primary values of this brief preliminary analysis may be able to provide a greater degree of freedom for the concert hall designer and a better way to correct existing halls with low volumes and low reverberation times. Essert has done commuter modeling on simple forms, with spaciousness showing up as the only musical subjective quality consistently improved, but this study does not include elements found in real world concert, including side balconies and adjustable suspended canopies.[7] Note that the work of Davies and Cox in reducing seat-dip attenuation still has yet to be applied in a real concert hall.[8]

[1]T. Hidaka, L. L. Beranek., S. Masuda, N. Nishihara, and T. Okano, "Acoustical design of the Tokyo Qpera City concert hall, Japan," J. Acoust. Soc. Am. **107**, 340–367 (2000).

[2]C. M. Harris, "Acoustical design of Benaroya Hall, Seattle," J. Acoust. Soc. Am. **110**, 2841–2844 (2000).

[3]L. L. Beranek, *Music Acoustics, and Architecture* (Acoustical Society of America, New York, 1962).

[4]L. L. Beranek, *Concert Halls and Opera Houses: How they Sound* (Acoustical Society of America, New York, 1996).

[5]D. L. Klepper, "First Presbyterian Church, Stamford, Connecticut," J. Acoust. Soc. Am. **31**, 879–882 (1959). Forty-eight years of hindsight suggests the words "early sound energy" should have been used instead of "direct sound" throughout this paper.

[6]J. S. Bradley and G. A. Soulodre, "The influence of late arriving energy on spatial impression," J. Acoust. Soc. Am. **97**, 2263–2271 (1995); "Objective measures of listener envelopment,"J. Acoust. Soc. Am. **98**, 2950–2957 (1995); A. Abdou and R. W. Guy, "Spatial information of sound fields for room-acoustics evaluation and diagnosis," J. Acoust. Soc. Am. **100**, 3215–3227 (1996); T. Okano, L. Beranek, and T. Hidaka, "Relations among interaural cross-correlation coefficient ($IACC_E$), lateral fraction (LF_E), and apparent source width (ASW) in concert halls," J. Acoust. Soc. Am. **104**, 255–265 (1998).

[7]R. Essert, "Links between concert hall geometry, objective parameters, and sound quality," J. Acoust. Soc. Am. **105**, 985 (1999).

[8]W. J. Davies and T. J. Cox, "Reducing seat dip attenuation," J. Acoust. Soc. Am. **108**, 2211–2218 (2000); D. L. Klepper, "Comment on 'Reducing seat dip attenuation,'" J. Acoust. Soc. Am. **110**, 1260 (2001); W. J. Davies and T. J. Cox, "Response to 'Comments reducing seat dip attenuation,'" J. Acoust. Soc. Am. **110**, 1261–1262 (2001).

[9]I make no claims to be a structural engineer, and obviously many variables will affect the actual cost comparison of a given proposed rectangular and inverted-V hall situation. Materials, required snow and rain loads, nature of joining planes at intersections, even ground conditions, and the required foundations (controlling lateral thrust in addition to providing ordinary support) can affect the comparison. However, the point that costs can be controlled by varying the apex angle remains valid.