The design of a multifunctional exhibition hall

When acoustics integrate with the structural design.
1. Introduction
2. Precedent
3. Design scope
4. Theoretical framework
5. Concept design
6. Final design
7. Impressions
8. Conclusion
9. Questions
“What are the characteristics of a multifunctional exhibition hall of which the structural design is integrated with the variable acoustical design and of which the acoustic properties are used as decisive factors in the visual appearance of the design?”
2. Precedent

UNESCO conference hall

UNESCO Conference building (1953) in Paris by Pier Luigi Nervi
(source: www.architetti.rieti.it/galleria.php)

Bending moment

Tensile stress

Building section

UNESCO Confrence building (1953) in Paris by Pier Luigi Nervi
(source: www.architetti.rieti.it/galleria.php)
3. Design scope

Location

Building:
- WTC-Expo, Leeuwarden

Properties:
- Height: 8 meters
- Surface: 13,005 m²
- Volume: 182,070 m³

Desirable improvements:
- Improve sound insulation
- Increase height to min. 14 m
- Adjustable light plan
3. Design scope

Location
3. Design scope

Location
### 3. Design scope

#### Program of requirements

<table>
<thead>
<tr>
<th>Function</th>
<th>Floor surface [m²]</th>
<th>Room volume [m³]</th>
<th>Room height [m]</th>
<th>Visitors</th>
<th>Reverberation time [s]</th>
<th>Objective clarity (C) 500/1000 Hz</th>
<th>Loudness (G) 500/1000 Hz</th>
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<tbody>
<tr>
<td>Exhibition</td>
<td>13.005</td>
<td>182.070</td>
<td>&gt; 14,0</td>
<td>10.710</td>
<td>n.a.</td>
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<td>Amplified music</td>
<td>6.500</td>
<td>84.500</td>
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<td>5.355</td>
<td>1,0 - 1,6</td>
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4. Theoretical framework

**Acoustics**

Standing wave reflections

Reflections types

Sound speed

$$C = f \times \lambda$$

- $C =$ speed
- $f =$ frequency
- $\lambda =$ wave length
4. Theoretical framework

**Acoustics**

**Reverberation time**

\[ T = \frac{1}{6} \times \frac{V}{A} \]

- \( T \) = reverberation time
- \( V \) = volume
- \( A \) = absorption surface

**Clarity**

Objective clarity (dB) = \( \frac{\text{Energy arriving within 80 ms of direct sound}}{\text{Energy arriving later than 80 ms after direct sound}} \)

**Envelopment**

Objective envelopment = \( \frac{\text{Energy arriving within 80 ms of direct sound}}{\text{Total energy arriving within 80 ms of direct sound}} \)

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4. Theoretical framework

**Acoustic shapes**

- **Source**
- **Direct sound**
- **Lateral reflections**
- **Receiver**

- **Shoebox**
- **Hexagonal shape**
- **Fan shape**
- **Reversed fan shape**
- **Horse shoe shape**
- **Elliptical**
- **Shoebox with arch (receiver in centre)**
- **Shoebox with arch (receiver out of centre)**
- **Shoebox with pinched roof**

**Existing hall types**

**Roof structures**
4. Theoretical framework

**Acoustic shapes**

- Shoebox
- Hexagonal shape
- Fan shape
- Reversed fan shape
- Horse shoe shape
- Elliptical
- Shoebox with arch (receiver in centre)
- Shoebox with arch (receiver out of centre)
- Shoebox with pinched roof
4. Theoretical framework

Folding techniques
4. Theoretical framework

**Folding techniques**

- **90 degree angles**
- **60 degree angles**

**Extra surface direction**

- Direct sound
- Lateral reflections
4. Theoretical framework

Folding techniques

90 degree angles

60 degree angles

Extra surface direction

Source

Receiver

Source

Receiver

Source

Receiver

Source

Receiver

Source

Receiver

Direct sound

Lateral reflections

Direct sound

Lateral reflections

Direct sound

Lateral reflections
5. Concept design

**Concept**

Dynamic exterior

Dynamic interior

Icon for the city

Multifunctional

- Exhibitions or festival: 13,005 m²
- Amplified music (concert): 6,500 m²
- Acoustic function: 1,710 m²
- Speech function: 1,710 m²
5. Concept design

Folding pattern

1. Valley fold

2. Mountain fold

α
5. Concept design

Shape variants

a = 3 meters

a = 4 meters

a = 5 meters
5. Concept design

Acoustical analysis

3 meter model

4 meter model

5 meter model

3 meter model

4 meter model

5 meter model

3 meter model

4 meter model

5 meter model
5. Concept design

**Acoustical analysis**

- **Objective clarity (C80)**
  - -1 to -3 dB
    - 3 meter model
    - 4 meter model
    - 5 meter model

- **Loudness (G)**
  - 7 dB
    - 3 meter model
    - 4 meter model
    - 5 meter model

- **Reverberation time**
  - 1.5 - 2.9 seconds
    - 3 meter model
    - 4 meter model
    - 5 meter model
5. Concept design

**Force flows**

- **Vertical displacement [m]**
  - Min: -0.1393
  - Max: 0.0075139

- **Horizontal displacement [m]**
  - Min: -0.12299
  - Max: 0.087236

- **Minimum principal stress [Pa]**
  - Min: -1.101e8
  - Max: 4.6327e6

- **Maximum principal stress [Pa]**
  - Min: -9.7354e7
  - Max: 6.2448e7
5. Concept design

Materialization

Reference curve

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<thead>
<tr>
<th>Octave bands</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
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<td>69.7</td>
<td>78.4</td>
<td>95.1</td>
<td>125.3</td>
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</table>

Section 1: 17 mm GFRP, 200 mm Rigid polyurethane foam, 17 mm GFRP

Section 2: 17 mm GFRP, 200 mm Rigid polyurethane foam, 17 mm GFRP

Section 3: 17 mm GFRP, 85 mm Rigid polyurethane foam, 30 mm Mineral wool, 17 mm GFRP

Section 4: 17 mm GFRP, 200 mm Rigid polyurethane foam, 30 mm Mineral wool, 17 mm GFRP

Section 5: 17 mm GFRP, 30 mm Mineral wool, 170 mm Rigid polyurethane foam, 17 mm GFRP

Section 6: 17 mm GFRP, 5.2 mm ISOMAT KE, 240 mm Rigid polyurethane foam, 17 mm GFRP

Section 7: 17 mm GFRP, 260 mm Hard rock wool, 17 mm GFRP
6. Final design

Situation plans

- Existing hall
- Exhibition hall
- Acoustic music hall
- Concert hall
6. Final design

Side wall

Acoustic music hall
*Height: 15 meters*

Concert hall (amplified music)
*Height: 15.5 meters*

Exhibition hall
*Height: 26 meters*
6. Final design

Building process

Phase 1
Foundation, floor and rails.

Phase 2
Mounting half a rib on the floor and fixing the mounting shoes.

Phase 3
Second half of the rib is mounted and connected with a hinge.

Phase 4
Placing the rib onto the supports.

Phase 5
Connecting ribs with composite hinges.

Phase 6
Finishing the main structure.

Phase 7
Placing the side walls.

Phase 8
Placing the external insulation slabs and door.
6. Final design

**Detail**

- **Brick pavement**
- **Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)**
- **Concrete floor slab (100 mm)**
- **Rockwool insulation (45 mm)**
- **Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)**
- **Stainless steel support (400 x 700 x 145 mm) on bearings**
- **Plastic layer to prevent thermal bridges (5 mm)**
- **Pin to fix the support in place**
- **Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)**
- **GFRP plastic shell (17 mm), Hard rockwool core (260 mm)**
- **External insulation slabs (45 mm glass wool sealed by 2 mm flexible rubber layer on both sides)**
- **Stainless steel rails (with cutouts for water drainage and fixation of the hinges)**
- **Stainless steel support (400 x 700 x 145 mm) on bearings**
- **Soil**
- **Composite hinge developed by D. Vosmaer**
- **Plastic profile (part of the profile used to fix the external insulation slabs)**
- **Plastic profile (part of the profile used to fix the external insulation slabs)**
- **Profile to fix the external insulation slabs (profile can rotate in one direction)**
- **Plastic profile (part of the profile used to fix the external insulation slabs)**
- **Polyurethane insulating lost casing (EPS) (80 mm)**
- **Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)**
6. Final design

**Detail**

- **Brick pavement**
- **Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)**
- **Polystyrene insulating lost casing (EPS) (80 mm)**
- **Concrete floor slab (100 mm)**
- **Rockwool insulation (45 mm)**
- **Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)**
- **Stainless steel support (400 x 700 x 145 mm) on bearings**
- **Stainless steel rail (with cutouts for water drainage and fixation of the hinges)**
- **L-profile (to mount the sidewalls to the structure)**
- **External insulation slabs (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)**
- **GFRP shell (17 mm), hard rockwool (400 / 200 mm), with a plastic profile (part of the profile used to fix the external insulation slabs)**
- **Steel shoe (connected to the support with hinges used to fix the slabs to the support)**
- **Plastic layer to prevent thermal bridges (5 mm)**
- **Profile to fix the external insulation slabs (profile can rotate in one direction)**
- **Composite hinge developed by D. Vosmaer**
- **Plastic profile (part of the profile used to fix the external insulation slabs)**
- **GFRP plastic shell (17 mm), Hard rockwool core (260 mm)**
- **Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)**
- **Rockwool insulation (45 mm)**
- **Concrete floor slab (100 mm)**
- **Polystyrene insulating lost casing (EPS) (80 mm)**
- **Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)**
- **Soil**
6. Final design

Detail
6. Final design

Detail

External insulation slabs (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)

Steel shoe (mounted on the GFRP panels and connected to other shoes with hinges) (1000 x 250 mm)

Profile to fix the external insulation slabs (profile can rotate in one direction)

Composite hinge developed by D. Vosmaer

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Steel hinge (d = 200 mm)

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Plastic profile to fix the external insulation slabs

Plastic profile (part of the profile used to fix the external insulation slabs)
6. Final design

**Detail**

- Telescopic arms to fix the angle of the GFRP panels (d = 40 mm)
- Hinged connection
- Plastic profile (part of the profile used to fix the external insulation slabs)

**External insulation slabs** (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)

**GFRP plastic shell** (17 mm), **Hard rockwool core** (260 mm)

**Plastic profile** (part of the profile used to fix the external insulation slabs)
6. Final design

Acoustical design

Acoustic music function

Speech function

Speech:
- Basis sound
- Speech hall
- Acoustic hall

Guitar:
- Basis sound
- Acoustic hall
6. Final analysis

**Structural analysis**

- **Vertical displacement [m]**
  - max 0.28 m < 0.34 m

- **Horizontal displacement [m]**
  - max 0.09 m < 0.09 m
6. Final Analysis

Acoustical analysis

- C80-value: -0.80 dB
- C50-value: 2.01 dB
- Reverberation: 2.28 seconds
- Reverberation: 0.78 seconds
- Loudness: 5.09 dB
- Loudness: 4.79 dB
7. Impressions

Acoustic music hall

Concert hall (amplified music)

Exhibition hall
7. Impressions

Exhibition hall
7. Impressions

Concert hall (amplified music)
7. Impressions

Acoustic music hall
“What are the characteristics of a multifunctional exhibition hall of which the structural design is integrated with the variable acoustical design and of which the acoustic properties are used as decisive factors in the visual appearance of the design?”
9. Questions