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Acoustic properties of calcium silicate ducts used for ventilation and smoke extraction

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Abstract
New trends in construction such as lightweight building and user requirements for more effective constructions result in the need for increased accurate design of solutions. With respect to the boundaries of a compartment within a building, each penetration can affect the acoustic and fire integrity. This paper deals with the impact on the integrity of a building compartment when ducts for normal ventilation and for smoke extraction are penetrating the walls and ceilings.
Two main properties are considered: a) the lateral transmission through the duct between two rooms and b) the risk that noise within a duct radiates to a room. With this study it is possible to evaluate the impact of ventilation and smoke extraction ducts on the acoustic integrity without the need for extensive sound test campaigns for each configuration installed. Because of the understanding built in this paper, fewer sound tests can be required to cover all applications.

Keywords: Calcium silicate, duct, break in/out; flanking transmission.

1 Introduction

Worldwide building trends forecast an increasing demand for faster and lighter building methods. But, dry-wall structures and modular building methods can be challenging for achieving simultaneously various performances, such as acoustics, fire safety, energy efficiency and stability. Therefore, more and more attention is required for accurate design of solutions. Within this scope, this paper deals with the integrity of dry-wall partitions that are penetrated by ventilation and smoke extraction ducts. Such penetrations cause specific challenges on the different mentioned building performances, but with most severe conditions for acoustics and fire. Some of the aspects studied can also be used for other types of enclosures, other than dry-wall partitions.
Building construction is strongly impacted by the new challenges to build more sustainable solutions. Hence, also new challenges are required for building compartments. And new challenges mean new design and solutions that can affect the essentials performances of the enclosures of building compartments, such as mechanical strength, thermal insulation, fire resistance or acoustic insulation.
Today fire is one of the essential performances for which the technical dimensioning is a priority (e.g. as found in building codes and mentioned in the Construction Products Regulation of Europe [14]). One of the most efficient solution for fire protection is to use high performance calcium silicate panels. It is mandatory to protect the occupants and rescue teams against the spread of a fire and smoke within and outside the building, as well as the collapse of the building. Structural stability can be achieved by protecting the structure when needed by cladding, mortars or intumescent paints. Another level of protection can be found in appropriate smoke management. A way to address this is by smoke extraction ducts that travel through the

building and as connected to a fan can extract the smoke away from the building. This approach has advantages for fire safety as occupants have smoke free escape routes and emergency teams can locate the fire in a fast way. In addition, such systems can limit the damage from smoke. Smoke extraction systems are often mandatory in public buildings by fire regulation.

As those smoke extraction ducts are exposed to high temperatures and they move hot smoke through the building, such ducts can be fabricated of PROMAT calcium silicate boards that can sustain temperatures well above 1000°C. In fact, the fire resistance of such systems needs to be proofed by fire tests in accordance to EN standards EN1366-1[11], EN1366-8 [12] and EN1366-9[13]. These real scale fire tests examen the fire performance of the ducts under high pressures and standard fire exposures. Pass criteria are given to maximum temperature increases and smoke leakage. When applied in a building, the layout of the ducts could be that they are connected to a central vertical shaft or that they cross multiple so-called fire compartments. A fire compartment is a zone in a building to where the spread of fire and smoke is limited. Typical examples are one hotel room, one apartment, one floor level in a building with a maximum size. Once different compartments are crossed with a duct, the penetration should be fire sealed around the duct and depending on the situation also a fire damper should be installed inside the duct.

With respect to acoustics, two main problems are identified and studied in this paper. First, the lateral acoustic transmission along the duct material and directly through its created wall penetration, by which sound can travel between the adjacent rooms. Second, the radiation of a noise originated within the duct towards a connected room through the in/outlet vents. In this latter case, the noise can come from the fan or from another room that is also connected to the duct. This problem is characterised as sound reduction break-in / break-out. Experiments are conducted in a full-scale acoustic test chamber.

Hence, the paper contributes to understand the critical design parameters and as such predict the impact of ventilation and smoke extraction ducts on the global sound insulation of the building when penetrating any fire compartment.

2 Identification of acoustic propagation paths in duct systems

For the case of ventilation ducts, acoustic problems could come from (1) operating service noise and/or (2) penetration of the ventilation duct through walls and ceilings.

For operating noise services, the fan will generate the highest noise level. A solution can be found in providing acoustic silencers positioned near the fan and downstream the duct trajectory towards the building rooms. Such a silencer can kill most of the fan generated noise. Further downstream the duct trajectory, other parameters can regenerate noises; so-called *regenerated noises*. Air flow speed, changes in duct direction and reductions in duct diameters are all possible reasons to have regenerated noises within the ventilation duct. The material used to construct the duct panels and their joints can have a significant impact on the perception of duct operating service noise. The role of the duct panel is to reduce the sound transmission from inside to outside of the ventilation duct and this is called noise *break out*. It also happens that a noise from a noisy room can penetrate the ventilation duct and this is called the noise *break in*. Both phenomena, further illustrated in Figure 1, can be solved if the airborne sound insulation of the duct panel is adequate.

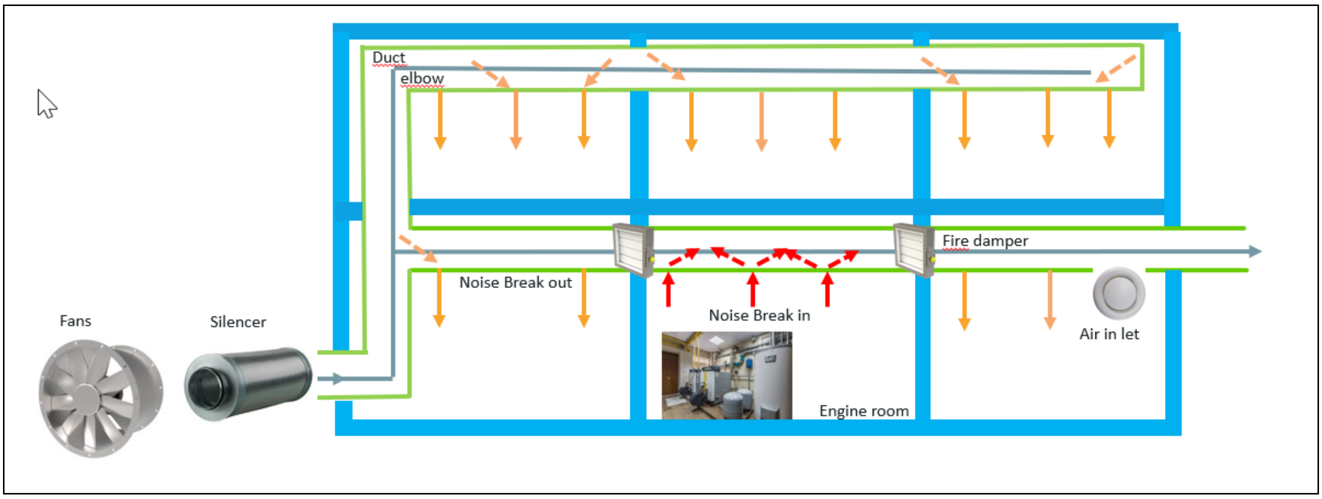


Figure 1 – Scheme of impact of background noise due to operating noise of extraction and ventilation duct.

The second type of acoustic problem that can result from ventilation ducts is the impact from its penetration through the walls and ceilings. Because of the penetration, there is a risk of downgrading the initial overall performance of the airborne sound insulation of the walls or ceilings that separate the rooms. This sound propagation path is called *lateral flanking airborne insulation* along the ventilation duct and is illustrated in Figure 2. Even here the panels used to build the ducts have a major role. But in addition, also the airtightness of the perimeter of the penetration can be a major down-grader of the acoustic performance. This is the reason why acoustic testing should be representative for the actual on-site installation.

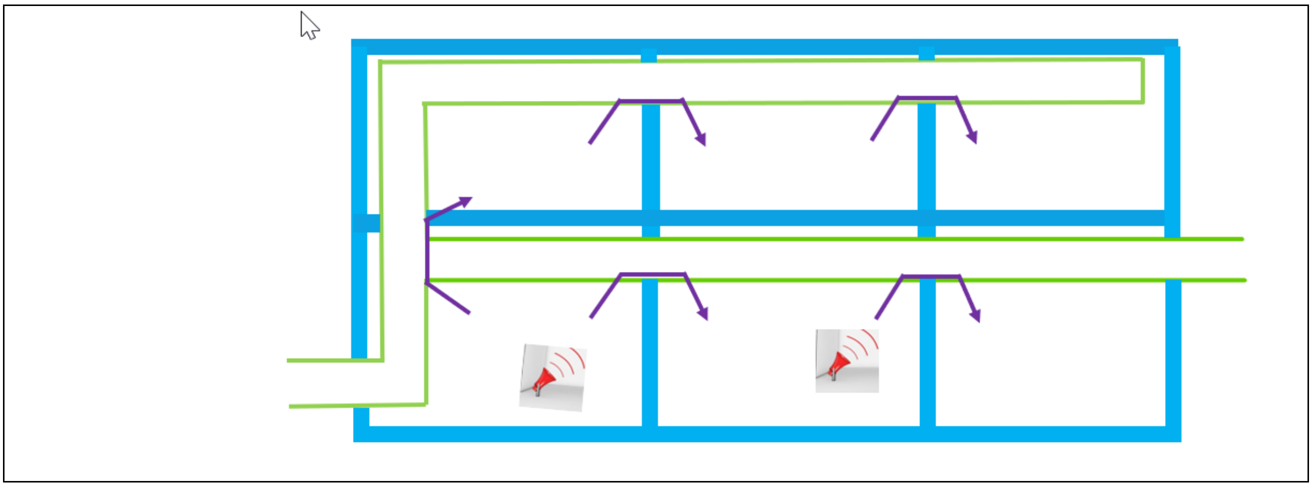


Figure 2 – Scheme of lateral flanking sound transmission due to duct penetration of the compartment boundaries.

3 Break in /Break out performance to reduce operating noise of ventilation and smoke extraction duct

The noise generated in a duct is mainly generated by the fan, which can be solved with silencers as discussed above. But, further efforts are necessary to carefully treat the as-mentioned regenerated noises. This type of noise can be treated by appropriate design of the duct panels. In this way, sufficient sound reduction can be achieved to cancel noise regenerated by dampers, reductions in duct cross-section and changes in network direction. The acoustic performance of the duct panel from which the duct is constructed, is therefore an important element in the acoustic dimensioning of ducts.

3.1 Dimensioning of background room noise

The minimum performance of airborne sound reduction that is required depends on the type of background noise and the relevant room type. In ASHRAE [1], a distinction of background noise per room type is found, as well as the related permissible sound levels (see Table 1).

Table 1 – Noise level criteria as specified in ASHRAE [1].

		Octave Band Analysis[a]	Approximate Overall Sound Pressure Level[a]	
Room Types		**NC/RC[b]**	**dBA[c]**	**dBC[c]**
Rooms with intrusion from outdoor noise sources[d]	Traffic noise	N/A	45	70
	Aircraft flyovers	N/A	45	70
Residences, apartments, condominiums	Living areas	30	35	60
	Bathrooms, kitchens, utility rooms	35	40	60
Hotels/motels	Individual rooms or suites	30	35	60
	Meeting/banquet rooms	30	35	60
	Corridors and lobbies	40	45	65
	Service/support areas	40	45	65
Office buildings	Executive and private offices	30	35	60
	Conference rooms	30	35	60
	Teleconference rooms	25	30	55
	Open-plan offices	40	45	65
	Corridors and lobbies	40	45	65
Courtrooms	Unamplified speech	30	35	60
	Amplified speech	35	40	60
Performing arts spaces	Drama theaters, concert and recital halls	20	25	50
	Music teaching studios	25	30	55
	Music practice rooms	30	35	60
Hospitals and clinics	Patient rooms	30	35	60
	Wards	35	40	60
	Operating and procedure rooms	35	40	60
	Corridors and lobbies	40	45	65
Laboratories	Testing/research with minimal speech communication	50	55	75
	Extensive phone use and speech communication	45	50	70
	Group teaching	35	40	60
Churches, mosques, synagogues	General assembly with critical music programs[e]	25	30	55
Schools[f]	Classrooms	30	35	60
	Large lecture rooms with speech amplification	30	35	60
	Large lecture rooms without speech amplification	25	30	55
Libraries		30	35	60
Indoor stadiums, gymnasiums	Gymnasiums and natatoriums[g]	45	50	70
	Large-seating-capacity spaces with speech amplification[g]	50	55	75

ASHRAE[1] also proposes a calculation method as given in Equation 1 to determine the resulting pressure level L_p in the room. The airborne sound reduction R_w of the duct panels is an important input parameter in this equation. The calculated transmission path corresponds to the mentioned sound break in. It is noted that VDI 2081 [2] proposes a similar model.

$$L_p = L_{w(in)} + 10\log\left(\frac{S^*}{A}\right) - R_w\text{-}10\log(\pi r L) \qquad (1)$$

With:

$L_{w(in)}$	is sound power level within the duct
S^*	is the effective surface of the duct
A	is the equivalent absorption of the receiving rooms
R_w	is sound reduction of the duct panels
r	is the distance from the duct
L	is the length of the duct

Rearranging the parameter of Equation 1 results in Equation 2 that allows to calculate the sound break out that considers the case when noise is re-injected in the duct. Again the airborne sound reduction of the duct panels is an important input parameter. When the noise level in the room is measured, it is possible to predict with Equation 2 how much noise will be re-injected in the ventilation duct.

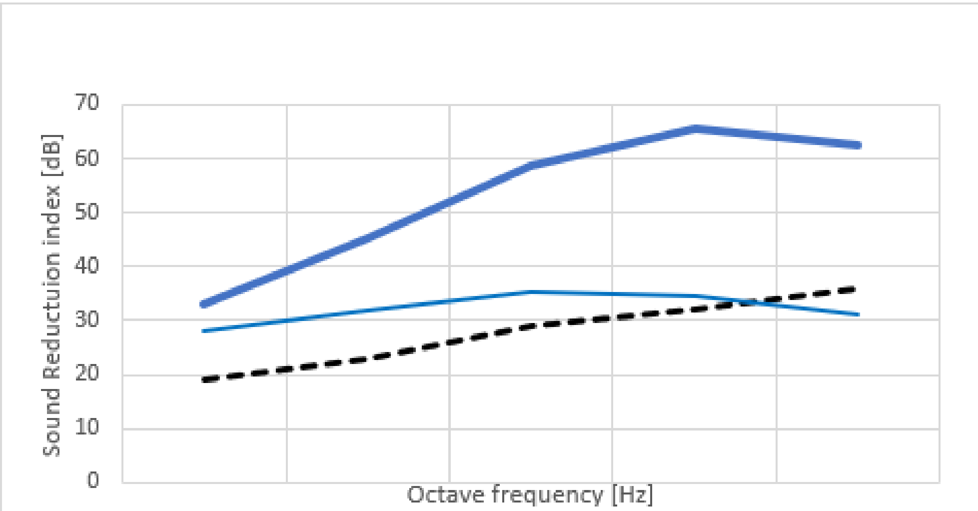
$$L_{w(in)} = L_p - 10Log\left(\frac{S^*}{A}\right) + R_w + 10Log(\pi r L) \tag{2}$$

In conclusion, both equations present a simple tool to predict the sound level whatever the sound level is entering (break in) or leaving the duct (break out). Those equations confirm the importance of having an adequate airborne sound reduction of the duct to prevent induced acoustic problems of service and background noise.

3.2 Data and tests of airborne sound reduction of duct panels

The VDI 2081 [2] presents some attenuation for different duct panel materials. However, there are no values for panels made from high-performance calcium silicate. This is the reason why laboratory tests were executed by the authors in compliance with ISO 10140-5 [3] and ISO 717_1 [4]. Table 2 presents the test results of metal sheet duct in comparison to ducts made of fire-resistant calcium silicate. For the latter, two configurations as depicted in Figure 3 are studied. First, the calcium silicate panel is used on its own, whereas in the second, an acoustic and aesthetic lining is added to improve further the acoustic performance and keep the level of fire resistance. The results in Table 2 show that when a higher acoustic performance is needed, it is possible to reinforce the acoustic lining to eliminate all risks of break in and break out.

Table 2 – Comparison of the performance of a metal duct panel with a calcium silicate duct panel and its upgrade with an additional lining (values in dB).



		125	250	500	1000	2000	Rw
Duct Steel sheet panel (---)	1 mm	19	23	29	32	36	31
Duct calcium silicate pannel (___)	30 mm	28	31,9	35,5	34,6	31	35
Reinforce duct (______)	110 mm	33	45,2	58,8	65,6	62,4	57

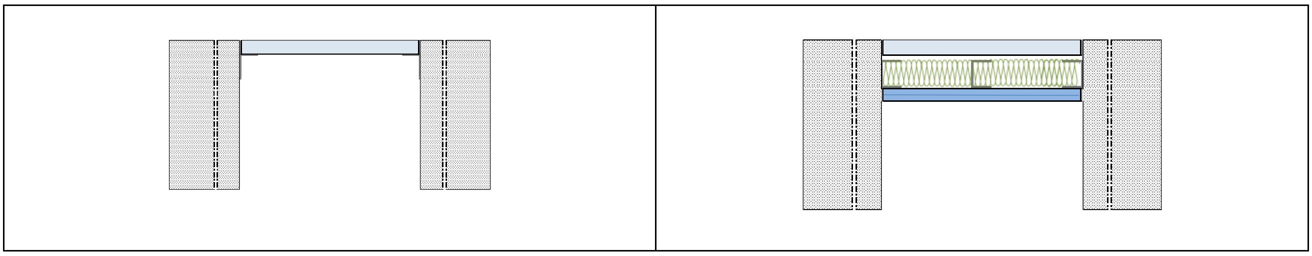
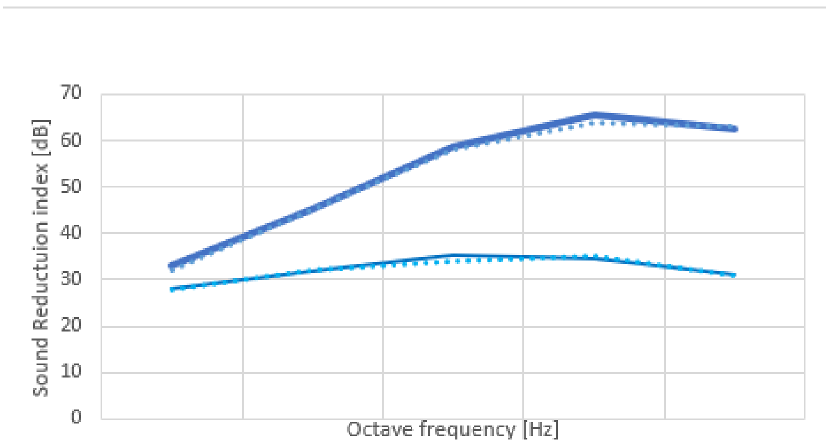


Figure 3 – Drawing of tests configuration – Left: single calcium silicate duct panel – Right: acoustic lining on calcium silicate panel.

3.3 Numerical model of sound reduction of duct panels

The acoustic performance of the panels can be assessed with a numerical model [6]. Table 3 confirms for the calcium silicate duct panels and their additional lining the good agreement between numerical simulations and actual sound tests. The use of this kind of models, makes it possible to design the best solution for the acoustic lining in agreement with the specific acoustic objectives related to break in and break out. This approach is also useful to select the most relevant options prior to laboratory sound tests.

Table 3 – Comparison of the modelled and tested sound reduction of duct panels (values in dB).



			125	250	500	1000	2000	Rw
Test	Duct calcium silicate pannel (___)	30 mm	28	31,9	35,5	34,6	31	35
Model			28	32	34	35	31	
Test	Reinforce duct (______)	110 mm	33	45,2	58,8	65,6	62,4	57
Model			32	45	58	64	63	

3.4 Examples of background noise calculations

Table 4 presents examples of background noise calculations by using Equation 1 and the comparison with the given background noise criteria from ASHRAE. Cases 1 and 3 consider only break out, whereas cases 2 and 4 considers in addition break in due to adjacent machine rooms. The calculations show that metal sheet panels are too weak to reach the requirements of background noise level for case break out (cases 1 and 3). The calcium silicate panel can pass the requirements for break out, but the upgrade of the lining is required to pass both break in/out.

Table 4 – Example of background noise calculation for different cases of break in/out (values are in dB).

Case of study	Duct panel design	Break out Lwin	Break in Lw Machine	Lp Room 2	NC Criteria	Results
1	1 mm steel duct panel	50	n/a	27	25	Not passed
2	1 mm steel duct panel	50	50	35	25	Not passed
3	30 mm calcium silicate panel	50	n/a	24	25	Passed
4	30 mm calcium silicate panel with reinforced lining	50	50	24	25	Passed

4 Impact on acoustic integrity of building compartments due to lateral flanking transmission from ventilation and smoke extraction ducts

Another sound transmission path could occur when a ventilation duct passes through walls or ceilings. Consequently, in some cases the apparent performance of the main ceiling or wall will be reduced due to the duct penetration.

4.1 Calculation of compartment integrity performance with duct penetration.

The standard [5] EN12354 gives an equation to calculate the impact of a ventilation duct that passes through walls or ceilings, reproduced hereafter as Equation 3. The calculation is based on a simplified model that is presented in the standard. Thanks to this equation, the noise impact of the smoke extraction and ventilation duct when pentrating the walls and ceilings can be calculated.

$$R'_W = -10Log\left(10^{-\frac{R_W}{10}} + 10^{-\frac{D_{n,f,w}+10Log\left(\frac{l_{lab}}{l_{test}}\right)+10log\left(\frac{S_s}{A_0}\right)}{10}}\right) \quad (3)$$

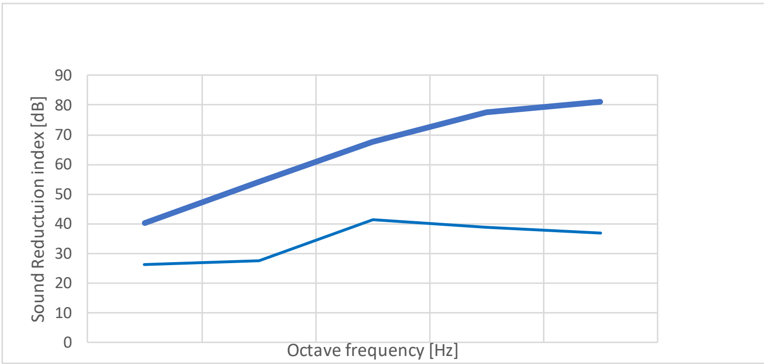
With:
- R'_w is the weighted apparent sound reduction index for overall transmission [dB]
- R_w is the weighted flanking sound reduction index for direct transmission [dB]
- $D_{n,f,w}$ is the weighted flanking sound reduction indirect transmission path [dB]
- L_{lab} is the laboratory test length [m]
- L_{test} is the rel duct length [m]
- S_s is the area of the separating element [m²]
- A_0 is the equivalent absorption area (10 m²) [m²]

4.2 Test results and enhancing solution

Although the impact on the acoustic performance of lateral flanking transmission of smoke extraction or ventilation ducts can be significant, neither the VDI 2081 [2] or ASHRAE [1] provide performance examples. This is the reason why sound tests were performed by the authors. The tests were realized in compliance with ISO 101848-1 [7], ISO 101848-2 [8] and ISO 717_1 [4].

Table 5 presents some results for calcium silicate duct panels. It is noted that no data has been found on metal sheet ducts. It is found that for some relevant cases, the performances of calcium silicate panels may not be enough to maintain the initial performance of the separating element. In those cases, similar as in previous section, the performance could be adequately improved by reinforcing the acoustic lining and as such eliminating all risks of downgrade of the initial acoustic performance of the main walls and ceilings. Figure 4 shows on the left the layout of the studied standard calcium silicate duct and on the right the layout including the additional acoustic lining.

Table 5 – Performance of lateral flanking transmission of calcium silicate ducts with and without acoustic lining.



		125	250	500	1000	2000	Dnfw
Duct Steel sheet panel (---)	1 mm	No Data	No Data	No Data	No Data	No Data	No Data
Duct calcium silicate pannel (___)	30 mm	26,3	27,5	41,2	38,7	36,7	38
Reinforce duct (_______)	110 mm	40,1	53,9	67,6	77,5	81	65

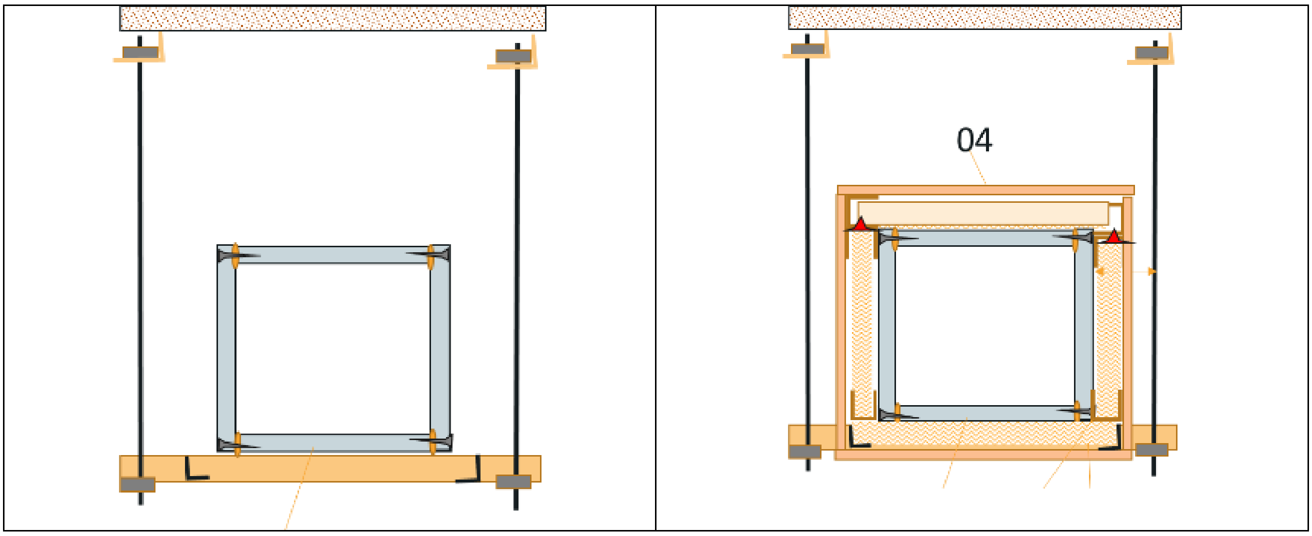


Figure 4 – Tested configuration – Left: calcium silicate duct with typical structure of assembly – Right: calcium silicate duct with additional acoustic lining.

4.3 FEM model of lateral flanking transmission test

As there is no model available in design codes to the lateral flanking transmission tests of ventilation and smoke extraction ducts, a numerical acoustic model was developed in COMSOL 5.6 [10]. The FE model couples Pressure Acoustics in the Frequency domain with a Structural interaction by using Solid Mechanics. As mentioned above such model can help in the design and understanding, nonetheless a sound test is required as a model is based on assumptions and simplification of complex phenomena and geometry. At this

stage, it is studied what the prediction accuracy could be of such kind of models. Therefore, the model result is compared with experimental data.
In Figure 5, the geometry and the used boundary conditions of the model are illustrated. A duct with size 1.32 x 1.07 x 9.26 m is made of 35 mm calcium silicate boards and penetrates a wall at its midspan. The model represents a duct that connects a source room and a receiving room.

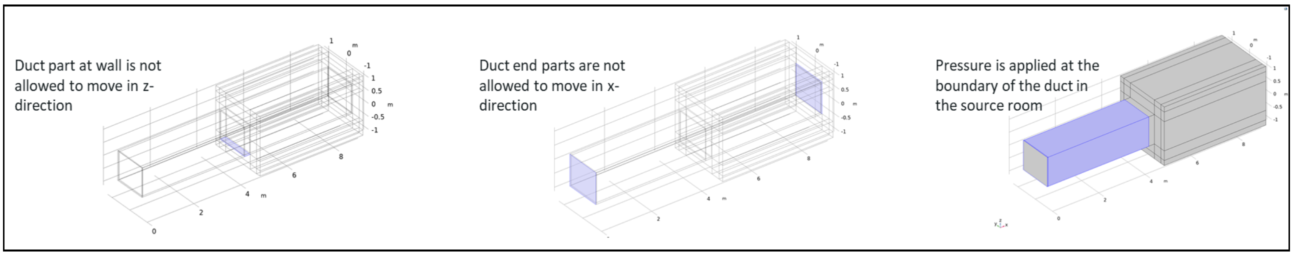
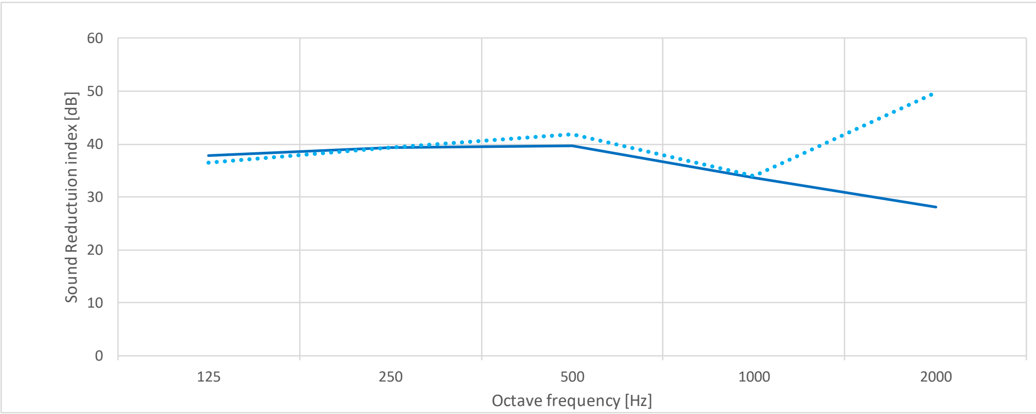


Figure 5 – Geometry and boundary conditions of the duct model

The sound pressure is directly implemented on the boundaries of the duct part in the source room by a sum of a number of uncorrelated plane waves moving in random directions, representing an ideal diffuse acoustic field [10]. The receiving room is modelled using Perfectly Matched Layers (PML). The wall at midspan is only represented by the restriction in movement of the duct in z-direction. This approach allows to simplify the geometry of the connected rooms and as such limit the computational demand. Further simplifications are found in modelling only the duct boards without their actual fixations (such as staples, glue), joints and considering 100% air tightness of the system.
The sound reduction index is calculated as $10*\log_{10}(P_{in}/P_{tr})$ [dB] with P_{in} the total incident power at duct boundaries source room and P_{tr} the total transmitted power at duct boundaries in receiving room. The sound waves are impacting directly on the duct and the sound is then transmitted to the other chamber by conduction through the board and the generated air waves inside the duct. Table 6 illustrates the result when compared to experimental data. Up to 1000 Hz Octave frequency the model can capture well the test result. Beyond this Octave frequency, deviation is found that can be attributed to a too coarse mesh due to limitation of computational power.

Table 6 – FEM simulation of the lateral flanking transmission by the duct, in comparison to test data



			125	250	500	1000	2000
Test	Duct calcium silicate pannel (___)	35 mm	37,9	39,4	39,7	33,7	28,1
Model	(.....)		36,4	39,3	41,9	33,9	49,7

4.4 Example of calculation of the impact of duct lateral flanking transmission on wall and ceiling performance

Table 7 presents some examples of calculation of downgrading the main walls or ceiling due to lateral flanking transmission based on Equation 3. When the lateral flanking transmission is much below the performance of the walls or the ceilings, it is observed that the overall performance R'_w is limited to the performance of the weakest element. To conclude, it is necessary to have a lateral flanking transmission performance adapted to the wall or the ceiling that is penetrated.

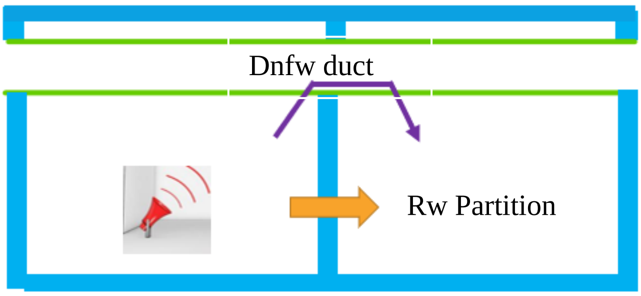


Figure 7– Scheme of the direct sound transmission of the separating element and the lateral transmission path of the ventilation duct.

Table 7 – Calculation of sound reduction due to lateral and flanking transmission, with ventilation and extraction duct (all values are in dB).

Case of study	Duct panel design	Rw of walls or ceiling	Dnfw of duct	Global R'w
1	Calcium silicate 30 mm	40	38	37
2	Calcium silicate 30 mm	60	38	41
3	Calcium silicate 30 mm with reinforced lining	40	68	40
4	Calcium silicate 30 mm with reinforced lining	60	68	60

5 Conclusions

This paper presents an overview of the acoustic dimensioning of ventilation ducts. Additional data has been presented based on sound tests on ducts fabricated from calcium silicate technology. Present study has shown that on the first acoustic problem of break in/out, calcium silicate panels can provide better airborne sound insulation to operating service noise with respect to metal sheet ducts because they are heavier. In this way, the risk of being disturbed by ventilation noises is drastically reduced. It is shown that for relevant cases where acoustic performance requirements are utmost severe, the acoustic requirement can be achieved easily by adding an additional lining. This lining can at first stage be dimensioned by using acoustic numerical models.

The second acoustic challenge is to ensure that when the ducts pass through a wall or ceiling, it will not downgrade the airborne sound insulation of the separating element. Results have shown that the risk exists that the duct decreases the initial airborne sound insulation performance of the separating walls and ceilings. Also for this acoustic problem, an upgrade of the lining of the calcium silicate duct results in adequate acoustic performance. For the moment, there is no reliable model to design the solution for this type of sound problem, although some promising FEM results were discussed. Lateral transmission sound tests are required to study this acoustic problem.

Acknowledgements

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