Application of aerogel-based plaster towards thermal retrofit of historical facades: A computational assessment

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Abstract

The retrofit of historical facades of the building stock has grown in importance due to energy efficiency considerations in the building sector. Among other recent new construction technologies, aerogel-based plaster systems with high thermal insulation have been developed in the past few years by the AEC-industry. Although still rather expensive, these systems offer opportunities to insulate highly-articulated historical facades in compliance with the principles of heritage protection.

This contribution analyses the effect of the application of such aerogel-based plasters on historical building facades in terms of thermal bridges. Thermal bridges are considered to be of high importance for both the building’s overall energy performance and the quality assurance in terms of healthy indoor environment. The latter includes aspects of interior surface temperatures, condensation risk, and mould growth. Typical construction details of historical building facades were selected based on relevant literature. These details were analysed and evaluated with the help of a numeric thermal bridge simulation tool. A set of scenarios including original state and different retrofit measures were applied to these details and their effect was evaluated in view of thermal bridge calculation. This contribution includes – along with basic information about the aerogel-plaster systems and related background – description of the methodology and a discussion of the results.

1. Introduction & Background

An incontrovertible fact in the ongoing discussion about climate change and global energy consumption is that buildings have a major share of both energy consumption and emission of climate-harming substances (DENA, 2013). There are multiple strategies to reduce the energy demand of buildings: one of the most common and obvious tactics is the insulation of the building envelope. While this can be generally realized for new buildings, older buildings with strongly-articulated and historical meaningful facades require sophisticated approaches. Typical insulation panels would lead to a loss of the architectural value of such buildings, and is thus forbidden by relevant authorities (BDA, 2011).

One option for thermal retrofitting of buildings with rich articulated facades are highly-insulating plasters. Typical insulation plasters are based on perlite. These plasters have been available on the market for many years, but possess only limited thermal insulation potential in comparison to insulation panels. A new development in the field of insulating plasters is plaster systems based on Silica aerogel. This material, explored already many decades ago (Kistler, 1931), is a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with air. Such structures offer, due to their high porosity, very low thermal conductivity. The present contribution analyses the effect of application of an aerogel-based plaster product to historical facades. The impact of the application to planar elements can be simply evaluated via the change in U-Value. In contrast, the impact of such systems on non-planar elements or component joints is not trivial. Thermal retrofit of non-planar elements is difficult both regarding building construction detailing as well as in view of assessing the impact of thermal bridges. Moreover,

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ill-conceived retrofitting concepts could even increase (as compared to pre-retrofit state) the effect of thermal bridges. Therefore, a numeric simulation tool is utilized to assess the impact of such highly-insulated plaster systems on thermal bridges in building envelopes.

The performance of five typical details from central-European historical buildings was evaluated without any improvement and under different improvement scenarios (application of perlite and aerogel plaster systems). To additionally be able to assess the impact of such options at the whole building level, a typical building from the "Gründerzeit" Vienna (historical building of around 1900) was used as a case study. For this building, the heating demand and transmission losses attributable to (2-D) thermal bridges were calculated via a simple normative procedure for its original state and different retrofit scenarios. The calculation method allows for different levels of inclusion of thermal bridges: Calculations were performed with “default” and with “detailed” consideration of thermal bridges.

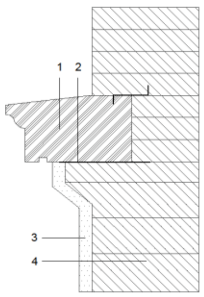
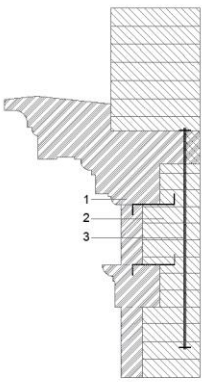
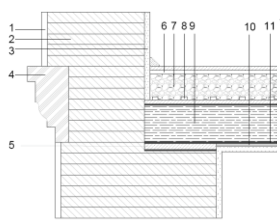
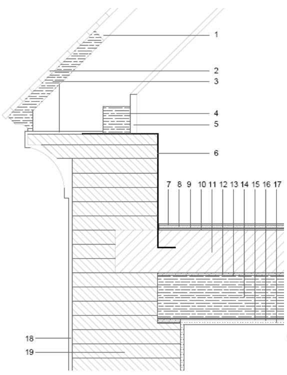
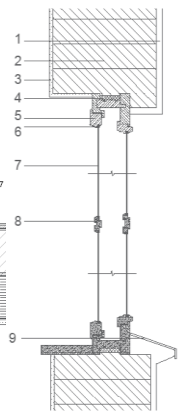
2. Methodology

2.1 Evaluated details

Five typical architectural details (Riccabona and Mezera, 2003; Eicke-Hennig et al., 1997) of historical buildings were used for the 2-dimensional thermal bridge evaluation (see Table 1):

Details 1-3 represent different cornice variants, including natural stone cornices with and without a steel anchor and a junction of a wooden slab next to a masonry cornice. **Detail 4** is the attic parapet junction with a ventilated roof. **Detail 5** represents a casement window and wall junction. The latter detail was examined both in terms of vertical and horizontal sections. The respective assumed material properties (Kornicki 2014) are summarized in Table 2.

Table 1 – Overview about evaluated details. The numbers in the illustrations refer to the assumed building material properties.

Detail 1	**Details 2**	**Detail 3**	**Detail 4**	**Detail 5**
Brick wall with natural stone cornice	Natural stone cornice with steel anchoring	Wooden slab with a gravel filling (with cornice articulation)	Ventilated attic with retrofitted ceiling slab	Casement window
				

2.2 Scenarios

For all five details retrofit scenarios were developed (Table 3). Scenario A for all details represents the pre-retrofit state. For Details 1-3 five different scenarios were generated and examined, while for Details 4 and 5 a further scenario was considered. For all scenarios the same boundary conditions within the applied linear thermal bridge evaluation were applied (θ_i = 20°C, θ_e = -10°C). Moreover, all details were assessed based on the same calculation settings concerning the level of detail and iterative calculation steps in the numeric thermal bridge simulation tool.

Table 2 – Material properties of the assumed building components (numbers refer to illustrations in Table 1).

	No. and Name of Material	λ [W.m^{-1}.K^{-1}]	μ [-]
Detail 1	1. Natural Stone	2.30	35
Detail 1	2. Reinforced Steel	60	100000
Detail 1	3. Lime cement plaster	0.90	15
Detail 1	4. Old brick masonry	0.71	8
Detail 2	1. Natural Stone	2.30	35
Detail 2	2. Old brickwork	0.71	8
Detail 2	3. Reinforced Steel	60	100000
Detail 3	1. Lime cement plaster	0.90	10
Detail 3	2. Old brick masonry	0.71	8
Detail 3	3. Gypsum plaster	0.80	10
Detail 3	4. Natural stone	2.30	35
Detail 3	5. Plank flooring	0.13	40
Detail 3	6. False Floor	0.13	40
Detail 3	7. Gravel filling	0.70	1
Detail 3	8. Wood	0.15	125
Detail 3	9. Hard Wood	0.185	100
Detail 3	10. Fire clay	0.75	1
Detail 3	11. Cardboard	0.17	50000
Detail 4	1. Air cavity	0.025	1
Detail 4	2. Roofing tile	0.7	10
Detail 4	3. Wood	0.15	50
Detail 4	4. Hard wood	0.182	125
Detail 4	5. Gypsum cardboard	0.21	10
Detail 4	6. Reinforced steel	60	100000
Detail 4	7. Coating	0.26	1
Detail 4	8. Concrete screed	1.4	50
Detail 4	9. Mineral wool	0.041	50
Detail 4	10.Lime Cement plaster	0.90	15
Detail 4	11.Reinforced concrete	2.3	100
Detail 4	12.Plank flooring	0.13	40
Detail 4	13. Cardboard	0.17	50000
Detail 4	14. Hard wood	0.182	125
Detail 4	15. Rough spruce formwork	0.14	50
Detail 4	16.Fire clay	0.75	1
Detail 4	17.Gypsum plaster	0.8	10
Detail 4	18. Lime cement plaster	0.90	15
Detail 4	19. Old brickwork	0.71	8
Detail 5	1. Lime cement plaster	0.90	15
Detail 5	2. Old brick masonry	0.71	8
Detail 5	3. Gypsum Plaster	0.80	10
Detail 5	4. PU-foam (R=55)	0.031	50
Detail 5	5.Wood (R=800)	0.8	50
Detail 5	6. Gluing material	0.001	50000
Detail 5	7. Air cavity	0.025	1
Detail 5	8. Glass (d=4mm)	31	10000
Detail 5	9. Air Layer	0.2	1

Table 3–Evaluation scenarios for the Details 1 – 5. (PW: planar wall, DE: decorative element, IR: Improved Roof, PP: Perlite Plaster, AP: Aerogel Plaster; SI: Styrofoam Insulation above cornice, IW: Improved Windows)

Scenario	Detail 1	Details 2	Detail 3	Detail 4	Detail 5
A			Original state of detail (prior to retrofit)		
B		PW: 50 mm PP		IR	IW
C		PW: 50 mm PP, DE 20mm PP & SI		IR, PW 50 mm PP	IW, PW 20 mm PP
D		PW: 50 mm AE		IR, PW: 50 mm PP DE: 20mm PP & SI	IW, PW 50 mm PP
E		PW: 50 mm AP DE: 20mm AP & SI		IR PW: 50 mm AP	IW PW 20 mm AP
F				IR, PW: 50mm AP DE: 20mm AP &SI	IW, PW 50 mm AP

2.3 Case study building

To assess the overall impact of the described retrofit strategies, they were applied virtually to a case study building Figure 1). This building is a typical Viennese residential building from around 1900 .

Fig. 1 – Case study building (left: front view, right: SketchUp-Model).

2.4 Cases

For the whole building evaluation, a set of different cases were calculated. These were based on the scenarios A (original state, referred to as case 1), C (case 2) and E (case 3). All these cases were calculated with two different approaches concerning thermal bridges

(i) Using the rough default estimation via the Austrian Standard B8110 (ASI, 2014)

(ii) Using detailed values for thermal coupling coefficients.

Results of the thermal bridge evaluation of details 1 – 5 were used for this calculation. For thermal bridges of the building envelope that were not evaluated in detail within this study, typical thermal coupling coefficients were used (Hauser & Stiegler, 2001; DIN, 2008). The evaluations were based on a climate data file for Vienna, Austria.

2.5 Applied evaluation tools & data exchange

The thermal bridge evaluations were performed with AnTherm 7.125 (Kornicki, 2014). The whole building evaluation including transmission loss and heating demand calculations was based on the Austrian Energy Certificate method (OIB, 2011) as implemented in the software Archiphysik 11 (A-Null, 2014). For geometry modelling, SketchUp Make was used (SketchUp, 2014). The geometry model was then transferred to Archiphysik. For consideration of the thermal bridges the ψ-values results from AnTherm were added to the default thermal bridges library of Archiphysik.

3. Results & Discussion

3.1 Results of Thermal Bridges Evaluation

The application of insulation to the outer surfaces of the details results in the following:

- Improvement of U-Values of the undistorted "planar" building components.
- Changes in the values of indicators related to thermal bridges, i.e., thermal coupling coefficient (L2D according to ISO, 2008), ψ-values, and f_{Rsi}-values (ASI, 2014)

While the impact of insulation on the U-Value of the planar components is rather easy to capture, the effects related to thermal bridges require more detailed analysis. Table 4 illustrates all mentioned indicators for all details. Note that some indicators show two instead of one value: this is due to two adjacent building components to outside and two indoor spaces adjacent to the detail (Detail 3 & 4, upper component/upper room), or to results of different sections trough the detail (Detail 5, horizontal section mentioned first). Figure 2 illustrates the graphical output of the numeric simulation for Detail 1. Scenarios D and E involve a significant increase in indoor surface temperatures. Both Figure 2 and Table 4 show the improvement of the detail in terms of U-Value of planar components and thermal bridge indicators. Details 2, 3, 4, and 5 show f_{Rsi}-values below the standard thresholds (ASI, 2003) of 0.71 (mould grow) or even 0.69 (surface condensation) in some scenarios. The application of insulation in general seems to improve the thermal performance of the analysed junctions. The scenarios with applied Aerogel plaster insulation significantly decrease the thermal coupling coefficients of the details (28 to 71% improvement). The application of Perlite plaster in case of detail B does not raise the f_{Rsi} above the threshold value. The application of Aerogel plaster raises the f_{Rsi} above the threshold of 0.71. This might be due to the fairly large natural stone cornice part. In case of Detail 4, retrofitting only one adjacent building component (roof) might leave the thermal bridge critical. This suggests that treating single components of an existing building's envelope may lead to subpar performance. Rather, a detailed thermal bridge analysis should accompany all projected changes to existing building envelope construction details.

Furthermore, Table 4 illustrates that retrofit strategies that exclude articulated elements of the facades might offer reduce U-values of the planar components, but not necessarily reduce the impact of thermal bridges (this is, for instance, illustrated via the quite large ψ-values in the scenarios without insulation of decorative elements).

3.2 Results of building-related Heating demand and thermal transmittance

The case study building's heating demand and transmission losses were evaluated for case 1 – 3 with both approximated (using default values) and detailed thermal bridges. Building components adjacent to the thermal bridges evaluated within this contribution were considered with the U-values described in the sections before, while other components were assumed with default values (OIB, 2011). Table 5 offers an overview of the applied U- and g-values.

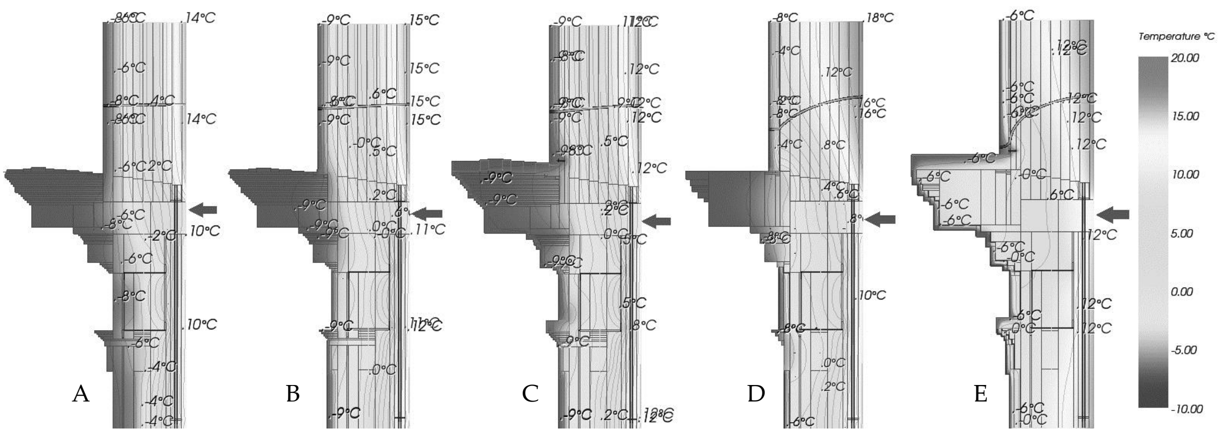


Fig. 2 – Simulation Output of Scenario A (left) to E (right) for Detail 1.

Table 4 – Results for details 1-3. Bold values in the f_{Rsi}-column imply condensation and/or mould growth risk. Data cells with two instead of one value represent two adjacent building components (Detail 3 and 4), two adjacent indoor spaces (Details 3 and 4), or details with more than one two-dimensional thermal bridge evaluation (Detail 5, horizontal and vertical sections). Values printed in bold letters indicate that they are below the f_{Rsi}-threshold values of 0.69 / 0.71.

Detail & Scenario		U-Value [W.m-2.K-1]	U-Value-Improvement	L2D [W·m-1·K-1]	L2D-Improvement	Ψ [W.m-1.K-1]	f_{Rsi} [-]
Detail 1	A	1.26	-	3.39	-	0.19	0.73
	B	0.93	26%	2.67	21%	0.31	0.77
	C	0.93	26%	2.55	25%	0.19	0.81
	D	0.37	71%	1.63	52%	0.71	0.81
	E	0.37	71%	1.13	67%	0.21	0.90
Detail 2	A	0.86	-	3.03	-	0.69	**0.62**
	B	0.70	19%	2.63	13%	0.82	**0.65**
	C	0.70	19%	2.62	14%	0.80	**0.65**
	D	0.33	62%	2.18	28%	1.18	0.72
	E	0.33	62%	1.58	48%	1.58	0.77
Detail 3	A	1.67 / 1.23	- / -	3.22	-	-0.09	**0.65** / 0.79
	B	1.19 / 1.13	29% / 8%	2.71	16%	0.07	0.73 / 0.85
	C	1.19 / 1.00	29% / 19%	2.54	21%	0.04	0.75 / 0.87
	D	0.43 / 0.37	74% / 70%	1.25	61%	0.38	0.79 / 0.90
	E	0.40 / 0.42	76% / 66%	1.07	67%	0.13	0.86 / 0.92
Detail 4	A	1.35 / 1.24	- / -	5.14	-	1.26	**0.70** / 0.79
	B	0.11 / 1.24	92% / 0%	2.63	49%	0.62	**0.71** / 0.79
	C	0.11 / 0.92	92% / 25%	2.05	60%	0.50	0.78 / 0.85
	D	0.11 / 0.92	92% / 25%	2.01	61%	0.40	0.79 / 0.85
	E	0.11 / 0.37	92% / 70%	2.02	61%	1.31	0.85 / 0.94
	F	0.11 / 0.37	92% / 70%	1.07	79%	0.40	0.86 / 0.67
Detail 5	A	1.20	-	3.64 / 8.62	-	1.29 / 3.84	**0.44** / **0.43**
	B	1.20	-	1.94 / 3.99	46% / 54 %	-0.27 / -0.86	0.73 / 0.74
	C	1.06	12%	1.79 / 3.67	49% / 57%	-0.30 / -0.52	0.76 / 0.76
	D	0.90	25%	1.62 / 3.52	55% / 59%	-0.32 / -0.35	0.78 / 0.76
	E	0.60	50%	1.29 / 2.89	65% / 67%	-0.36 / 0.46	0.78 / 0.76
	F	0.36	70%	1.06 / 2.47	71% / 71%	-0.39 / 1.01	0.78 / 0.76

Table 5 – U-Value [W.m^{-2}.K^{-1}] and g-value [-] assumptions for case 1-3.

Element		Case 1	Case 2	Case 3
$U_{ground\ slab}$	[W.m^{-2}.K^{-1}]	1.20	0.35	0.35
$U_{exterior\ wall}$		1.20	0.93	0.37
U_{window}		2.15	0.98	0.98
U_{roof}		1.35	0.11	0.11
U_{door}		2.50	1.70	1.70
g_{glass}	[-]	0.67	0.67	0.67

For the detailed calculation of the thermal bridges, the ψ-values illustrated in table 6 were used. Note that negative ψ-value results of the thermal bridge evaluation were set to zero to avoid inconsistency in heating demand calculation.

Table 6 – ψ-Values [W.m^{-1}.K^{-1}] assumed for case 1-3. Values written in italics indicate that these values were derived from thermal-bridge-calculations

Thermal Bridge		Case 1	Case 2	Case 3
$\psi_{cornice}$	[W.m^{-1}.K^{-1}]	*0.19*	*0.19*	*0.21*
$\psi_{window\ (vert)}$		*3.84*	*0.00*	*0.00*
$\psi_{window\ (hor)}$		*1.29*	*0.00*	*0.00*
ψ_{roof}		*5.04*	*0.40*	*0.40*
$\psi_{ground\ slab}$		0.65	0.65	0.65
ψ_{door}		0.10	0.10	0.10
ψ_{corner}		0.00	0.00	0.00
$\psi_{floor\ slab}$		0.60	0.60	0.60

The other, approximate approach uses an equation from an Austrian Standard (ASI, 2014) to derive a cumulative value for all thermal bridges within the building's envelope. This equation uses the conductance values and areas of the building envelope elements as input data.

Table 7 illustrates the results of the case study building evaluation for heating demand (HWB) and Linear transmittance of the thermal bridges.

While the absolute values of the approximation and the detailed calculation show differences, the percentages of improvement, especially for the heating demand, tend to be similar.

The approximation seems to offer sufficient accuracy for benchmarking purposes. However, for detailed thermal bridge evaluation and planning purposes, the detailed values from simulation or catalogues are indispensable.

Table 7 – Results for Cases 1-3 of overall heating demand and linear transmittance of thermal bridges.

	HWB [kWh.m^{-2}.a]		Linear transmittance [W.K^{-1}]	
	approx.	detailed	approx.	detailed
Case 1	316	387	329	541
Impr.	-	-	-	-
Case 2	207	229	241	357
Impr.	-35 %	-41 %	-27 %	-34%
Case 3	96	102	108	192
Impr.	-70 %	-74 %	-67 %	-64 %

4. Conclusion and Future Research

This contribution explored the application of Aerogel plasters to historical building envelopes. The application of such systems has a high impact on the thermal performance of both planar components and articulated architectural details. If properly planned, it is possible to significantly reduce both the building's heating demand and the impact of thermal bridges, without compromising the building's architectural appearance. Concerning the U-values of the planar surfaces of the examined details, a reduction of 26 – 71% could be realized with application of Aerogel plasters (Perlite plaster:19 – 26% reduction). The thermal coupling coefficients reduction by application of Aerogel-plasters ranges between 28 – 79% for the details (Perlite plaster: 13 – 61%).

However, an application of Aerogel plaster systems on heritage protected architectural buildings still requires specific approval by relevant authorities and might be hampered by the comparatively high price of aerogel plasters and the complexity of application.

Future research efforts in this field should address the following aspects:

- Broadening the scope of examined details based on typical construction details from different architectural époques that would allow a usage of Aerogel-plaster systems.
- 3D simulations of thermal bridges
- Conducting transient thermal performance simulations of the thermal bridges and comparison with measurements of corresponding details.

- The details illustrated in this contribution were retrofitted following straightforward approaches. There is, for sure, potential for more sophisticated solutions such as a partial material replacement, and detailing based on traditional techniques. For instance, the application of the plaster without edge profiles and stabilizing net should be explored via long-term-durability tests, as this seems to be important for retrofitting highly-articulated façade profiles.
- Currently, the behaviour of the Aerogel-plaster can be modelled in view of parameters such as conductivity, water vapour resistance, and specific heat. However, long-term monitoring of the thermal and hygric behaviour of the aerogel plaster in different scenarios, such as drought stress, high sun exposure, and wind-driven rain should be considered.
- To popularise aerogel plasters in the market, comprehensive efforts in communication, involvement, and coordination of all potential stakeholders of a retrofit processes (clients, craftsmen, and historical preservation officials) is required.

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