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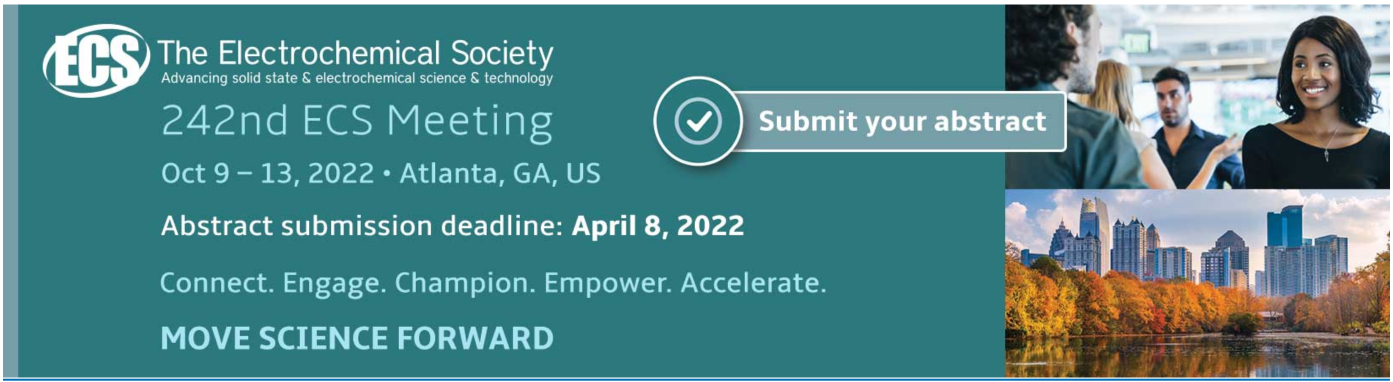

Thermal characterization of a multilayer coating for seismic and energy building renovation

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Abstract. Many buildings built in Italy in the 60s and 70s need an energy requalification and at the same time an improvement of the seismic behaviour. A non-invasive method for a joint requalification consists of an anti-seismic plaster layer and a thermal coating. In this work, a multi-layer package of 3 cm of SFRM coating and 8 cm of wood fiber placed on a 20 cm masonry wall is analyzed. Numerical and experimental analysis allowed to characterize the wall, and to determine the influence of the connecting elements.

1. Introduction

The importance of reducing the energy consumption of buildings is a well-known topic. Indeed, as stated by the European directive 2010/31/EU [1] on the energy performance of buildings, and even before by the famous EPBD 2002/91/EU [2], buildings are responsible for 40% of total energy consumption in the European Union. These directives, as requested, were implemented in Italy and, in particular, 2010/31/EC was implemented with the introduction of Ministerial Decree (DM) 26 June 2015 [3]. This regulation, given its importance, extensively deals with the issue of improving the performance of existing buildings: the energy performance of buildings must be improved, taking into account outdoor climatic conditions, indoor climate requirements and cost-effectiveness [4].

Another critical aspect of the old buildings realized in Italy in the 60s and 70s, often in masonry, is the seismic one. Therefore these buildings also need a seismic renovation.

In 2018 was published the Directive 2018/844 of the European Parliament and of the Council [5], which amends Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. It has the aim of accelerating the improvement of energy efficiency by integrating various aspects and it focuses to buildings with higher comfort levels and wellbeing for their occupants, according to the 2009 World Health Organisation guidelines. Recently, with the Decree Presidency of the Italian Republic (DPR) n. 48 [6], it has also been implemented in Italy. Among the innovations introduced, three are highlighted here: the creation of a National Portal on the energy performance of buildings; the request to define some typical improvement measures valid for building categories and climatic zones; the request to also check the seismic risk when carrying out an energy requalification intervention.

The SISMACOMF research project, carried out jointly by DICATAM (Department of Civil, Environmental, Architectural Engineering and Mathematics) and DIMI (Department of Mechanical and Industrial Engineering) of the University of Brescia, is precisely in the direction of an integrated seismic and energy requalification. The possibility of improving the seismic behavior of a building by means of a non-invasive technique that consists in applying a particular fiber-reinforced plaster on the external surface of the envelope was recently proposed by the research group of Structural Engineering of DICATAM [7] and thermal coatings, consisting in an insulating layer applied to the outer surface of the wall, are frequently used to enhance the energy performance of existing buildings. They are more efficient than internal insulation systems because they significantly reduce the thermal bridges. Hence the idea of jointly carrying out seismic and energy renovation, through an appropriate multilayer package. The SISMACOMF project addresses buildings built in Italy in the 60s and 70s, with the aim of carrying out seismic and energy requalification with a package of maximum thickness of 11 cm and using natural and sustainable materials as much as possible. The general characteristics of these buildings are collected in the UNI/TR 11552 technical report [8], therefore the research group of Thermal Science of DIMI proposed three packages that meet the criteria for the energy requalification of the opaque walls of these buildings in relation to the different Italian climate ~~areas~~ zones. These requirements are defined by the DM 26 June 2015. As concerns the opaque vertical envelope components of the existing buildings undergoing renovation, for energy upgrading interventions the thermal transmittance *U* must fulfil limit values, which are going to become stricter starting from 2021 (0.40 W/(m^2 K) for the climate zones A and B, 0.36 W/(m^2 K) for the climate zone C, 0.32 W/(m^2 K) for the climate zone D, 0.28 W/(m^2 K) for the climate zone E and 0.26 W/(m^2 K) for the climate zone F). The climate zones are defined by the Presidential Decree 26 August 1993, n. 412 [9] in terms of degree-days. In case of major renovations, also the overall heat transfer transmission coefficient value H'_T has to fulfil a limit value depending on the surface to volume ratio S/V and on the climate zone; moreover, for sites where the value of the average monthly irradiance on the horizontal plane during the month of highest summer insolation is greater than or equal to 290 W/m^2, it is required that the value of the mass per unit area M_s is greater than 230 kg/m^2, or that the value of the periodic thermal transmittance Y_{ie} is lower than 0.10 W/(m^2 K) for all the opaque vertical walls excluding those included in the northwest / north / northeast quadrant. Two of the proposed packages by the SISMACOMF project are suitable for climatic zones from A to E, allowing them to respect the limits of thermal transmittance for all construction types of the period of interest. Ad hoc solutions may be necessary in some cases only for zone F. To respect the maximum overall thickness of 11 cm, in the first package it was necessary to choose an innovative material, in particular the aerogel. The second package uses the more conventional wood fiber instead, but the overall thickness rises to 14 cm. The third package allows to respect the maximum thickness of 11 cm and to use wood fiber, but meets the requirements for thermal transmittance for all construction types of the period of interest only for climatic zones A, B and C. In addition, the three packages were designed so that they can also improve summer comfort, reducing and postponing the thermal peak of the central hours of the day, therefore also their periodic thermal transmittance was evaluated. In [10] also the acoustical performances of one of these packages was analyzed. In all packages connecting elements are needed both for fixing the Steel Fiber Reinforced Mortar (SFRM) coating layer and for the subsequent thermal coating. The connections act as point thermal bridges. Linear thermal bridges must be included in the calculations and their influence is shown for example in [11] and [12]. Point thermal bridges are neglected because their influence is usually minimal, as shown for example in [13]. However, since in this case the connections are numerous, it was decided to investigate their influence with this work. Therefore, as described in this article, one of the proposed packages has been numerically simulated using the Comsol Multiphysics software. Another objective of this work was to characterize the multilayer partition in the best possible way. Therefore the package was also realized and tested experimentally at the Pisa Laboratory of the University of Brescia. Both the transmittance *U* and the periodic transmittance Y_{ie} were determined, in order to characterize the behavior of the package both in stationary and dynamic conditions.

2. Materials and methods

The multilayer package object of this study consists of a 3cm thick coating made with SFRM and a 8cm thick layer of wood fiber, characterised by a density of 140 kg/m^3. SFRM was obtained by mixing a cement based ready-mix mortar with 60 kg/m^3 of high strength hooked-end steel fibers having a length of 32mm, a diameter of 0.4mm and a tensile strength of 2100MPa. Characterization tests carried out on SFRM prisms [7] showed the good tensile behavior of the material in the cracked stage as well as the moderate value of the elastic modulus (i.e. 20,400MPa), which is suitable to ensure a good masonry-to-coating compatibility. Moreover, the ability of SFRM coating to improve the seismic behavior of masonry structures was proved by performing a cyclic test on a full-scale hollow brick masonry building [14]. The latter was designed and tested as part of the SISMACOMF project for the energy renovation of italian masonry buildings constructed from '60s to '70s in climatic zones A, B and C. The multilayer package described above is the most representative retrofitting solution developed in the SISMACOMF project for hollow brick masonry. As example, a bare wall made of 20 cm-thick hollow bricks is considered here.

2.1. Analytical characterization

For a multilayer wall of homogeneous layers, the thermal transmittance U depends upon the characteristics of the composing layers and, according to the ISO 6946 [15] standard, should be determined for a steady condition as $U = (R_{s1} + R_1 + R_2 + \ldots + R_N + R_{s2})^{-1}$. R_1, R_2, …, R_N are the thermal conductive resistances of the single layers, defined as the ratio between the thickness and the thermal conductivity, whereas the terms R_{s1}, R_{s2} are the surface resistances of the boundary layers, including convection and radiation.

The periodic thermal transmittance Y_{ie} depends upon the characteristics of the composing layers, but also depends on the arrangement of the layers and should be determined, according to the ISO 13786 [16], considering time-dependent sinusoidal boundary conditions. The periodic thermal transmittance Y_{ie} correlates the specific heat flux on a side to the temperature variation on the opposite side of the wall and is defined as $Y_{ie} = -\, q''_i/T_e$, where T_e is a sinusoidal function and T_i is considered constant. The thermal admittance correlates the specific heat flux to the temperature variation on the same side of the wall. The internal thermal admittance is defined as $Y_{ii} = q''_i/T_i$, where T_i is a sinusoidal function and T_e is considered constant, the external thermal admittance is defined as $Y_{ee} = q''_e/T_e$, where T_e is a sinusoidal function and T_i is considered constant. These three terms, Y_{ii}, Y_{ee}, Y_{ie}, can be determined by the heat transfer matrix method.

This approach was used to analyze the multilayer wall composed of homogeneous layers, without the presence of the connecting elements. For inhomogeneous layers, where inhomogeneity is due to thermal bridges, the ISO 6946 and ISO 13786 are the references standards again, but the methods described above are no longer applicable and it is necessary to carry out numerical simulations.

2.2. Experimental characterization

A 110 cm × 120 cm wall was built at the Pisa Laboratory of the University of Brescia.

The first layer of plaster for seismic renovation is fixed to the hollow brick wall by means of steel anchors with a diameter of 6 mm and a length of 6 cm applied every 40 cm approximately. The thermal coating of wood fiber is fixed by nylon anchors with a diameter of 10 mm applied every 30 cm approximately: the length of 14 cm is sufficient to cross both the coating and the SFRM coating. In this way also the thermal coating is anchored to the existing masonry. However, all the connecting elements represent thermal bridges. Finally, a layer of finishing plaster is applied.

Figure 1 shows the test wall poroton side (internal) and insulating side (external) and the details of the connections for fixing the anti-seismic plaster layer.

The tests are performed using a climatic chamber Angelantoni CH1200SP, three heat flow meters Hukseflux BSR240, two aluminium probes for environmental temperature LSI Lastem BST105, two slat probe in silver-plated copper for surface temperature LSI Lastem BST123 and a data logger LSI Lastem BABUC/A BSA014. The wall to be tested was mounted in place of the climatic chamber door, so the hot chamber was represented by the climatic chamber and the cold chamber by the laboratory room, equipped with a heat pump.

Figure 1. From left to right: the test wall poroton side (internal) and insulating side (external), the connections for fixing the SFRM coating.

With this instrumentation, the temperature are measured with an uncertainty of 0.5 K. For the specific heat flow, the uncertainty is obtained by dividing the measurement uncertainty of the voltages, equal to 0.017 mV, by the sensitivity of the heat flow meters, between 0.06 and 0.07 mVm^2/W depending on the probe, and is about 0.25 W/m^2. By adding to this value the uncertainty due to the representation of the specific heat flow by the BABUC/A, which is 1 W/m^2, a total of about 1.25 W/m^2 is obtained.

To measure the total resistance of the wall R_{tot}, the temperature of the climatic chamber was set at 60 °C and maintained for ten days, necessary for the achievement of the steady state given the high thickness of the wall. The total resistance was determined with the progressive averages method, dividing the difference between the two surface temperatures by the specific heat flux. Since two heat flow meters were positioned on the internal surface of the wall and one on the external one, the calculation was carried out with the three different values and then the mean value was determined.

To measure the periodic thermal properties, the sinusoidal trend $T_i = T_m + T_a \sin(2\pi t/P)$ was imposed at the temperature of the climatic chamber, where T_m is 30 °C, T_a is 20 °C and P is 86400 s. The measure lasted ten consecutive days to allow a stabilized periodic regime. For inhomogeneous walls, the standard ISO 13786 defines the periodic thermal conductances L_{ii}, L_{ie}, L_{ei} and L_{ee}. $L_{ii} = q_i/T_i$ and $L_{ee} = q_e/T_e$ correlate the heat flux to the temperature variation on the same side of the wall, whereas $L_{ie} = -q_i/T_e$ and $L_{ei} = -q_e/T_i$ correlate the heat flux on a side to the temperature variation on the opposite side of the wall. They are complex quantities, therefore their module and phase should be determined from the sinusoidal functions of heat fluxes and temperatures. Since it is possible to impose a sinusoidal trend on the temperature of the climatic chamber T_i but not on that of the laboratory room T_e, only L_{ii} and L_{ei} could be determined. In order to determine L_{ee} ad L_{ie} it would be necessary to mount the wall with the surface of the thermal coating towards the climatic chamber, but this was not done for time reasons. The heat flow meters actually measure the specific heat flux at their position, therefore it was decided to still determinate the periodic thermal transmittance Y_{ei} and the periodic thermal admittance Y_{ii}, which can be seen as local equivalent values: in particular, two values for Y_{ii} were determined, given that two heat flow meters are positioned on the internal surface of the wall.

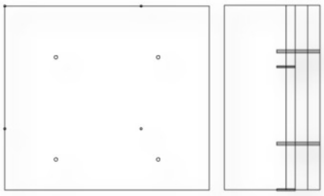

Figure 2. Schematic representation of the calculation domain for the multi-layer wall.

2.3. Numerical characterization

A calculation domain of 54 cm width and 60 cm height was chosen, which represents a quarter of the extension of the tested wall. These dimensions allow to exploit the two horizontal and vertical centerlines as symmetry planes, with a connecting element for the SFRM coating every 36 cm in the horizontal direction and every 40 cm in the vertical direction and a connecting element for the thermal coating every 27 cm in the horizontal direction and every 30 cm in the vertical direction (Figure 2). By means of the software COMSOL Multiphysics, conduction through the solid domain was simulated, imposing convective boundary conditions on the internal and external surfaces of the multilayer wall, while the lateral surfaces were considered adiabatic. The internal and external heat transfer coefficients were chosen in accordance with the ISO 6946 standard. The grid was built with elements with a maximum size of 20 mm and a minimum size of 1.5 mm. Where possible, the grid was obtained by extrusion in the direction normal to the wall, taking care to place at least three rows of cells in each layer.

To determine the total resistance R_{tot} and the transmittance U of the wall, a steady simulation was carried out, imposing a difference of temperature (T_i - T_e) of 20 K.

To determine the periodic thermal properties, two unsteady simulations were carried out, the first imposing $T_i = T_m + T_a \sin(2\pi t/P)$ and $T_e = T_m$, the second imposing $T_e = T_m + T_a \sin(2\pi t/P)$ and $T_i = T_m$, where T_m is 300 K, T_a is 100 K and P is 86400 s. Ten consecutive days were simulated in order to allow a stabilized periodic regime. Also in this case the thermal admittances and the periodic thermal transmittances Y_{ii}, Y_{ie}, Y_{ei} and Y_{ee} have been determined instead of the thermal conductances L_{ii}, L_{ie}, L_{ei} and L_{ee} introduced by the standard ISO 13786 for inhomogeneous walls. In the calculation, the values of the average specific heat flow on the internal and external walls were used, therefore the results can be seen as mean equivalent values.

3. Results and discussion

The characteristics of the multilayer wall, the analytical results and the numerical results are collected in Table 1, Table 2 and Table 3 respectively. By comparing the values in Table 2 with those in Table 3, it can be seen that the point thermal bridges have a negligible influence, although they are numerous. Note that the small differences between the values of the two tables are not due to the numerical resolution: simulations were also performed for the wall without the connection elements, obtaining results perfectly coinciding with the analytical ones in Table 1.

Table 1. Characteristics of the multilayer wall and thermal properties of the materials: the properties of the SFRM coating are hypothesized.

Layers	λ [W/mK]	ρ [kg/m³]	c [J/kg·K]	d [m]	d_{tot} [m]
Hollow bricks	0.252	817	840	0.200	0.310
SFRM coating	1.500	800	2200	0.030	
Wood fibre	0.040	140	2100	0.080	

Table 2. Analytical results: the corresponding total thermal resistance R_{tot} is 2.814 m^{2}K/W.

Property	Amplitude [W/m^{2}K]	Phase [h]
Internal thermal admittance Y_{ii}	2.574	2.074
External thermal admittance Y_{ee}	0.823	2.665
Periodic thermal transmittance Y_{ie}	0.042	12.211
Thermal transmittance U	0.335	---

Table 3. Numerical results.

Property	**Amplitude [W/m^{2}K]**	**Phase [h]**
Internal thermal admittance Y_{ii}	2.573	2.072
External thermal admittance Y_{ee}	0.828	2.663
Periodic thermal transmittance Y_{ie}	0.042	12.204
Periodic thermal transmittance Y_{ei}	0.042	12.203
Thermal transmittance U	0.336	---

The results of the experimental tests are collected in Figure 3 and Table 4. Figure 4 shows the method of progressive averages for the determination of the thermal resistance of the wall. It can be noted that different values are obtained by using the external specific heat flux, $R_e = 2.979$ m^{2}K/W, and the two values of the internal specific heat flux, $R_{i1} = 1.788$ m^{2}K/W and $R_{i2} = 2.261$ m^{2}K/W. The mean values for the internal specific heat flux is $R_i = 2.025$ m^{2}K/W. The total thermal resistance $R_{tot} = 2.502$ m^{2}K/W is obtained as the average of R_e and R_i. The maximum combined uncertainty is 11.5% for R_e and this value can also be considered valid for R_{tot}. The uncertainties of each measured temperature and of each measured specific heat flux were calculated by summing their type A and type B uncertainties. The uncertainty of the thermal resistance was then obtained by applying the law of propagation of uncertainty.

Table 4 shows the values of periodic thermal transmittance Y_{ei} and internal thermal admittance Y_{ii}. It can be noted that the two internal thermal admittance values, Y_{ii1}=5.107 W/m^{2}K and Y_{ii2}=4.349 W/m^{2}K, are quite different from each other. Their combined uncertainties are less than 0.1%. The periodic thermal transmittance Y_{ei} results 0.101 W/m^{2}K and is characterized by an higher combined uncertainty, 7.9%, because the amplitude of the external specific heat flux, about 2 W/m^2, is small compared to the accuracy of representation of the specific thermal flow of the data logger, which is of the unit. Type B uncertainties were calculated for each measured temperature and for each measured specific heat flux. The uncertainty of the periodic thermal transmittance and of the thermal admittances were then obtained by applying the law of propagation of uncertainty. Given that the values of q''_e are mostly between -4 W/m^2 and 0 W/m^2, it is difficult to recognize a periodic trend for the external specific heat flux. Furthermore, the temperature of the laboratory room T_e fluctuates during the day by about 4 °C. Therefore the experimental values of q''_e, recorded every minute, were treated with the moving average method on 15 values. The curves obtained in this way for the ten days were superimposed, as shown in Figure 4, and finally a sinusoidal function was chosen which approximates them. This function was used for the determination of Y_{ei}.

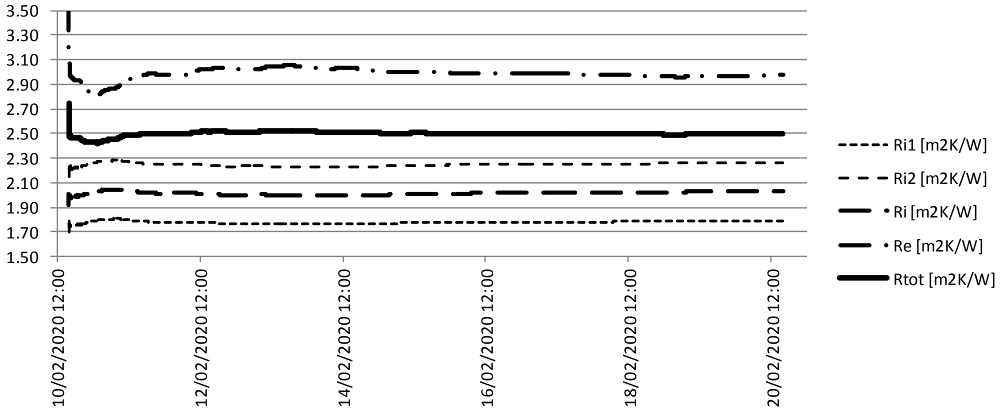

Figure 3. Experimental results: method of the progressive averages for the thermal resistance. It can be noted that different values are obtained by using the external specific heat flux, R_e, and the two values of the internal specific heat flux, R_{i1} and R_{i2}. The mean values for the internal specific heat flux is R_i, whereas the total thermal resistance R_{tot} is obtained as the average of R_e and R_i.

Table 4. Experimental results: dynamic properties and thermal transmittance. U is obtained from R_{tot} and from the values for surface resistances indicated in the standard ISO 6946.

Property	**Amplitude [W/m^{2}K]**	**Phase [h]**
Internal thermal admittance Y_{ii1}	5.107	2.808
Internal thermal admittance Y_{ii2}	4.349	2.943
Periodic thermal transmittance Y_{ei}	0.101	9.158
Thermal transmittance U	0.374	---

By comparing the experimental data (Table 4) with the numerical results (Table 3), it can be noted that the measured values of thermal transmittance U and periodic thermal transmittance Y_{ei} are greater than those obtained from the simulations. However, they appear in good agreement, also considering the difficulty of carrying out an experimental test on such a thick wall. The internal admittances Y_{ii1} and Y_{ii2} measured in correspondence of the two heat flow meters are quite different from each other and in any case much greater than that determined numerically. This can be partly explained by the presence of a layer of plaster on the real wall not inserted in the simulations. Regarding the value of the phase, the difference is probably due also to the daily fluctuations in the temperature of the laboratory room.

4. Conclusions

This work describes the thermal characterization of a masonry wall on which is applied a multilayer package designed for seismic and energy requalification. Both the SFRM coating and the subsequent thermal coating require numerous connection elements, which act as point thermal bridges. The comparison between the results of the analytical analysis of the multilayer wall without connection elements and the numerical simulations of the multilayer wall with the connection elements have shown that the influence of the connection elements is negligible both on the thermal transmittance U and on the periodic thermal transmittance Y_{ei} and its phase. Experimental tests performed on a wall built at the Pisa Laboratory of the University of Brescia showed a good agreement with the numerical simulations. Due to the high thickness of the wall, the time required for experimentation was high. Furthermore, the inhomogeneities in the wall make remarkable the influence of the positioning of the probes on the results.

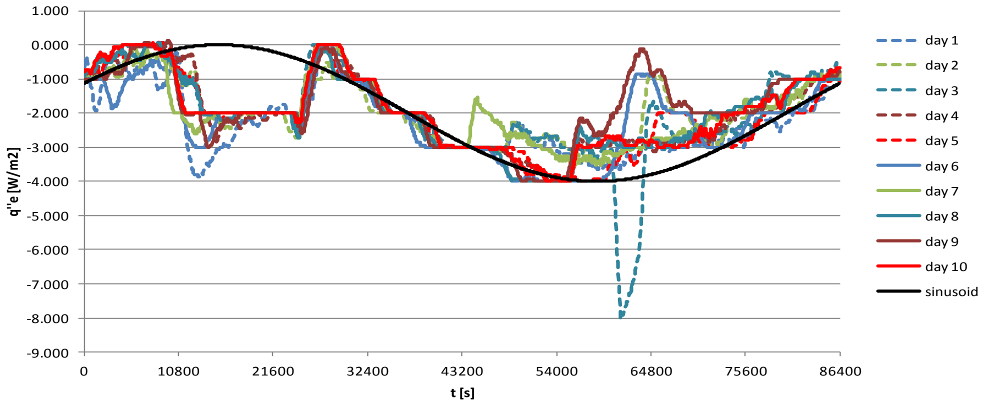

Figure 4. Determination of a sinusoidal function for the external specific heat flux.

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