

Thermal upgrade assessment of a multi-storey residential building based on *in situ* measurements

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Abstract. Within the framework of a renovation project in Stockholm area (Sweden), *in situ* measurements were carried out with the QUB/e method to (i) assess the actual thermal performance of the building fabric and (ii) validate the thermal upgrade measures implemented. Two consecutive QUB/e tests were performed in an apartment of a fully renovated multi-storey residential building. The average U -values were $0.64 \pm 0.04 \text{ W m}^{-2} \text{ K}^{-1}$ and $0.25 \pm 0.02 \text{ W m}^{-2} \text{ K}^{-1}$ for the glazings and the external walls, respectively. The measured values were in good agreement with the calculated values communicated by the municipality. A comparison of *in situ* measurements undertaken before and after the implementation of the thermal upgrade measures indicates that a three-fold decrease of the U -values (i.e., -67%) was achieved. This was consistent with the target set by the municipality (i.e., -60%). The thermal performance of the building fabric resulting from the thermal upgrade measures implemented (using off-the-shelf solutions) could thus be considered validated.

1. Introduction

The lack of fast, reliable yet practical *in situ* measurement methods often precludes the implementation of a systematic assessment of the thermal performance of the building envelope for both new-built and renovation projects. Several *in situ* measurement methods have been recently developed and/or improved to assess the thermal performance of buildings (e.g., see work carried out within IEA EBC Annex 58 on dynamic methods [1] and then further developed within IEA EBC Annex 71 – e.g., see [2,3]) but their use at a wider scale has not been achieved despite the interest expressed by industry. One of the most common factors restricting a wider uptake is the time required for such testing.

The QUB/e method [4,5] is a dynamic measurement method developed to estimate the thermal performance of building envelopes (i.e., whole Heat Loss Coefficient, HLC, and U -values) in a single night without occupancy. The QUB/e method differs from other measurement method in its speed: one single night compared to about two to three weeks for the most common *in situ* measurement methods (e.g., the coheating method [6,7] for the HLC and the heat flow meter method [8] for the U -values). This makes the QUB/e method suitable for large-scale use by industry to test the actual thermal performance of buildings. Its ability to provide reliable results was demonstrated experimentally in a climate chamber [4,5] and in the field [9,10] where its performance was compared against other existing methods.

Within the framework of a renovation project in Stockholm area (Sweden), *in situ* measurements were carried out with the QUB/e method to (i) assess the actual thermal performance of the building fabric and (ii) validate the thermal upgrade measures implemented.

This paper is organised as follows. The materials and methods used in this study are described in Section 2. The results obtained from *in situ* measurements are presented and discussed in Section 3. Concluding remarks can be found in Section 4.

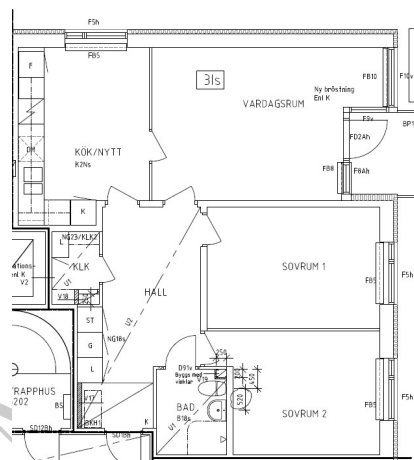
2. Materials and methods

2.1. Description of the building

The measurements took place in an apartment on the 10th floor of a circa 1960s multi-storey residential building located in Årsta (Stockholm area, Sweden). A view of the building and the layout of the apartment are shown in Figure 1.



(a) View of the external façade.



(b) Layout (sovrum = bedroom, kök = kitchen, vardagsrum = living room).

Figure 1. Overview of the apartment.

The wall construction is aerated concrete and the windows are double glazing units (DGU) with wood frames. The thermal upgrade measures involved an external wall insulation (EWI) system (Serporoc Premium/A system with glass wool from Isover and renders and other components from Weber) and the windows were made of quadruple glazing units (QGU) with aluminum frames (Domlux). The refurbishment process also addressed the airtightness of the building envelope to minimise infiltration losses and local thermal discomfort (e.g., at the vicinity of windows and balcony doors). The apartment has North – East orientation, floor area, attached area and net heated area of approximately 79 m², 193 m² and 241 m², respectively. It should be noted that the window-to-external wall ratio is quite high (i.e., 27%) and the proportion of the net heated area in contact with the exterior is low (i.e., 20% of the total net heated area) but typical for an apartment in a multi-storey residential building.

2.2. QUB/e method

The principle of the QUB/e method is relatively simple: (i) the interior of a building is subjected to a thermal load modulation composed of two phases of equal durations and with a constant power (i.e., heating and free cooling) during the night and without occupancy; (ii) the temporal evolution of the dissipated thermal power, the ambient air temperatures and the heat flux densities are measured; (iii) the thermal transmission properties of the building envelope are then derived.

The QUB/e method makes it possible to measure both the overall insulation level of the building envelope (i.e., whole HLC) and the local insulation level of building elements (i.e.,

U -values). For a detailed description of the QUB/e method and the associated theoretical developments, the interested reader should refer to [4, 5, 9–12] and references therein.

2.3. Monitoring equipment and testing protocol

The tests were carried out when the apartment was unoccupied between March 6th and March 9th, 2018. Two consecutive QUB/e tests were undertaken at night. The mechanical ventilation and the heating system of the apartment were switched off during the QUB/e tests. Electrical fan heaters (Honeywell HCE100 with a nominal power of 170/250 W) were placed in each room of the apartment in order to provide a uniform heating source for the QUB/e tests (the total heating power was 1.1 kW for each test). The total duration of each QUB/e test was 13 hours (i.e., between 5.30pm and 6.30am).

Heat flux plates (Hukseflux HFP01) and type K thermocouples were used to monitor the heat flux densities on building elements and the air temperatures. A silicone paste was used to ensure a good thermal contact between the heat flux plates and the building elements. All sensors were connected to data loggers (Graphtec GL820). Weather conditions (i.e., temperature, relative humidity, wind orientation and speed, solar radiation) were recorded with a Davis Vantage Pro2 weather station installed on the balcony of the apartment. The data acquisition rate was set to one minute.

In situ measurements of heat flux density, from which *in situ* U -values are derived, were taken at 20 locations on the thermal elements (6 on the external walls, 5 on the internal walls, 4 on the floor, 2 on the ceiling and 3 on the glazings) of the apartment using heat flux plates (HFPs). Only measurements of heat flux density obtained from those locations that were considered not to be significantly influenced by thermal bridging at junctions with neighbouring thermal elements (typically at distances greater than 500 mm from the junctions) were used in the calculation of the *in situ* U -values. The appropriate locations were determined through a thermographic survey undertaken in accordance with EN 13187:1999 [13] (not reported here for the sake of brevity). It should be noted that HFPs were placed at the centre pane of the windows, i.e. the U_g -value of these glazing units could be derived from our measurements.

During a QUB/e test carried out in an apartment located in a multi-storey residential building, the heat exchanges do not only occur between the interior of the apartment and the exterior environment but also between the interior of the apartment and the neighbouring internal zones (apartments, corridor). The whole HLC needs thus to be corrected [4, 5, 10] in order to report only heat losses (or gains) to the exterior environment and have a sound comparison with theoretical calculations which assume a uniform temperature within a building (i.e., there are no heat losses/gains).

The HLC with respect to the exterior environment can be calculated with the following formula:

$$HLC_{ext} = HLC_{raw} - \sum_j U_{eff,j} \times A_j \quad (1)$$

where HLC_{ext} , HLC_{raw} , $U_{eff,j}$ and A_j are the HLC w.r.t. the exterior environment only (in $W K^{-1}$), the 'raw' HLC (in $W K^{-1}$) obtained from the standard QUB/e analysis, the effective U -value of the j^{th} internal element (in $W m^{-2} K^{-1}$) obtained from the QUB/e method and the area of the j^{th} internal element (in m^2), respectively.

The effective U -values derived from the measurements on the HFPs located on internal building elements (internal walls, floor, ceiling) exhibited rather large variations so that the heat losses (or gains) associated with each internal element had a large uncertainty. Besides, the proportion of the net heated area in contact with the interior being large (i.e., 80%) and the building envelope being highly insulated (i.e., U -values for the external walls smaller than $0.3 W m^{-2} K^{-1}$), the estimate of HLC_{ext} would be associated with an uncertainty deemed not

acceptable. We will thus only present and discuss the U -values of the external walls and the glazings in the next section.

It should be noted that the difficulty associated with the characterisation of the HLC of apartments in multi-storey residential buildings is not only related to the QUB/e method but to dynamic measurement methods in general. For quasi steady-state measurement methods (e.g., coheating method), if access to neighbouring internal zones can be arranged to control/monitor the air temperatures (i.e., by prescribing the same setpoint temperature in each zone), the HLC to the exterior environment can be estimated. This is seldom possible in practice.

3. Results and discussion

3.1. Local U -values

Figure 2 shows the local U -values for the glazings and the external walls. Each boxplot corresponds to the U -values estimated for each QUB/e test for the glazings (3 different locations) and the external walls (6 different locations).

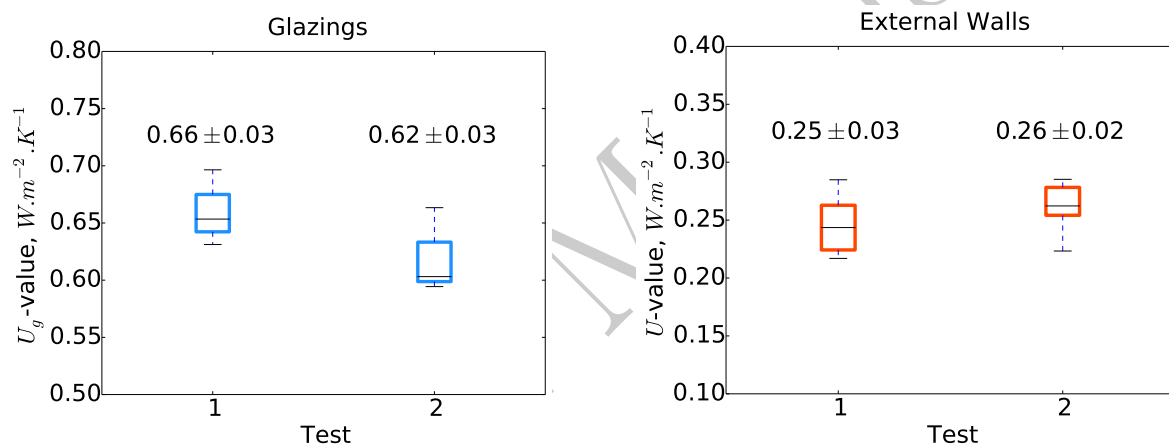


Figure 2. Local U -values. Each boxplot corresponds to the U -values estimated for each QUB/e test for the glazings (left) and the external walls (right).

The relative dispersion of the estimated local U -values was rather small (i.e., the coefficient of variation was smaller than 5% and 10% for the glazings and the external walls, respectively). This indicates that the building elements are fairly homogenous thermally-wise. This statement was backed-up by a thermographic survey undertaken in accordance with EN 13187:1999 [13] (not reported here for the sake of brevity).

The estimates obtained for both QUB/e tests are in good agreement (i.e., the relative differences are not significant) and demonstrate the robustness of the QUB/e method. The average measured U -values were $0.64 \pm 0.04 W m^{-2} K^{-1}$ and $0.25 \pm 0.02 W m^{-2} K^{-1}$ for the glazings and the external walls, respectively.

The measured values were in good agreement with the calculated values communicated by the municipality (i.e., 0.7 and $0.27 W m^{-2} K^{-1}$ for the glazings and the external walls, respectively). No 'performance gap' (e.g., see [14–16] and references therein) was observed (i.e., the relative differences between the target and the measured values were within the uncertainty bound of the measurements). The thermal performance of the building fabric resulting from the thermal upgrade measures (using off-the-shelf solutions) could thus be considered validated.

3.2. Thermal upgrade assessment

A comprehensive set of *in situ* measurements was carried out in an apartment before the implementation of the thermal upgrade measures [10]. The measurements presented in this paper were conducted in a different building, part of the the same refurbishment project in Årsta, since the renovation of the previously tested building was not yet completed at the time the measurements took place. If we assume that the thermal performance of the building fabric is homogenous within these multi-storey residential buildings, we can assess the actual thermal upgrade of the building envelope and compare it with the target value.

Figure 3 represents the average U -values (derived from *in situ* measurements carried out with the QUB/e method) of both the glazings and the external walls before (baseline) and after (retrofit) the implementation of the thermal upgrade measures. A three-fold decrease of the U -values (i.e., -67%) was achieved thanks to the thermal upgrade. This is consistent with the target set by the municipality (i.e., -60%).

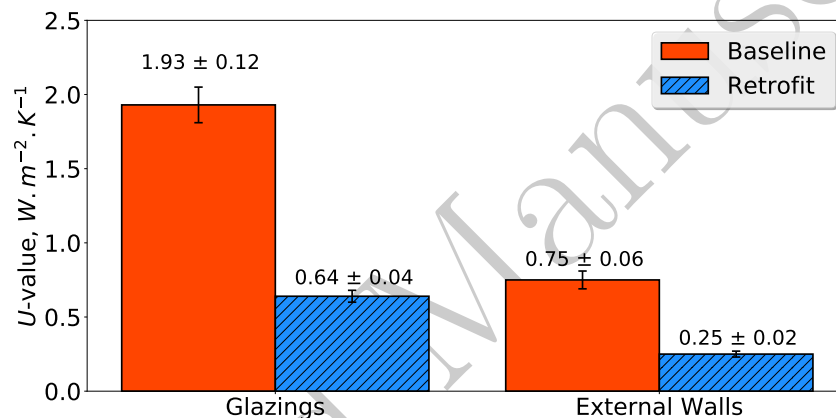


Figure 3. Average U -values before (baseline) and after (retrofit) the thermal upgrade measures.

4. Conclusion

The findings from a series of *in situ* measurements in a fully renovated multi-storey residential building were presented in this work. The objectives of the measurements were to (i) assess the actual thermal performance of the building fabric and (ii) validate the thermal upgrade measures implemented.

Two consecutive QUB/e tests were performed in an apartment located in Årsta (Stockholm area, Sweden) after its full renovation. We obtained robust estimates of the local U -values and the measured values were in good agreement with the calculated values communicated by the municipality.

A comparison of *in situ* measurements undertaken before and after the implementation of the thermal upgrade measures indicates that a three-fold decrease of the U -values (i.e., -67%) was achieved. This is consistent with the target set by the municipality (i.e., -60%). The thermal performance of the building fabric resulting from the thermal upgrade measures (using off-the-shelf solutions) could thus be considered validated.

This work demonstrated the relevance of the QUB/e method for wider uptake of quality assurance practices by the building construction industry.

A comprehensive evaluation of the building thermal performance should ideally include: (i) a statistical survey/sampling of the U -values (324 apartments were renovated in this project); (ii) an assessment of air leakages and thermal bridges (e.g., at the window-wall and

door-wall junctions); (iii) an appraisal of indoor environmental quality (IEQ). This thorough refurbishment performance evaluation will be conducted within the framework of the European Union's Horizon 2020 GrowSmarter project (<http://www.grow-smarter.eu/home/>).

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