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Published in:
6th International Building Physics Conference, IBPC 2015

Link to article, DOI:
10.1016/j.egypro.2015.11.003

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 830 – 835

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Building renovation with interior insulation on solid masonry walls in Denmark – A study of the building segment and possible solutions

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Abstract

The segment size of the Danish multi-story building stock from the period 1851-1930 is established through a unique major database managed by the Danish authorities. The outcome illustrates a large segment with 219,202 apartment units distributed over 14,832 unique buildings, all sharing characteristic geometry. Reduction of average U-value for the exterior façade is investigated in different dimensions, insulation degrees and thicknesses. The analysis shows that compared to insulation of only the infill walls below windows, fully covering insulation yields further 100-150% average U-value reduction. The large segment poses arguments for research into challenges raised by full surface insulation.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
Keywords: retrofit; interior insulation; theoretical analysis, saving potential; segment analysis;BBR

1. Introduction

To meet the general strive to reduce fossil fuels as an energy source in buildings, one of the methods is to apply thermal insulation. Appropriate levels of insulation of new buildings are regulated by legislation in Denmark, but buildings from recent decades only represent a limited fraction of the entire Danish building stock. The existing building stock, especially from the years before 1950, is considered to represent a huge potential for energy savings, based on the size of the segment and the potential of typical buildings in the segment [1-3].

The best solution from a building physics point of view is to insulate the exterior side of existing buildings [4-6]. Exterior insulation is, however, not suitable in all situations. A typical example is worth-to-preserve buildings, where preservation of original architectural features of the exterior facade are mandatory [7]. In the segment of worth-to-preserve buildings, occupants are able to obtain an indoor climate and comfort that meet modern requirements through interior insulation. However, interior insulation systems have a range of disadvantages that must be acknowledged: 1) Thermal bridges are not completely eliminated; 2) Reduction of the indoor space; 3) Alteration of interior expression; 4) Introducing risk of high moisture state in the materials.

The traditional Danish multi-story buildings from the period 1850-1930 is characterized by a large degree of repetition, with the same standard building technique used in complete districts of the cities. The buildings were typically made with facades of brick, with or without render, and with some wooden members, e.g. as supports of the floor beams. The floor decks were made with wooden beams that span perpendicularly between the façades, had wooden floorboards on top, wooden furring below as

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1876-6102
Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.003

underlay for the rendered ceiling, and clay pugging between the beams. This extensive use of well-proven techniques originates from strict legislation at the time, based on detailed regulation regarding their composition administered by the local authorities [8,9]. While the buildings in general are built after the same geometry and construction principles, each single building is characterized by geometrical differences between the floors. These principles are based on the goal of having smallest possible dimensions, to yield the highest floor space and lowest material usage.

With today's increasing focus on reduction of energy consumption, housing from this period has received increasing attention due to the large potential for energy and CO_2 saving [1-3]. The detailed regulated design makes it possible to develop a general method to insulate this segment, even though many construction details and large differences of the façade geometry at the individual floors make it necessary to adjust the individual solutions.

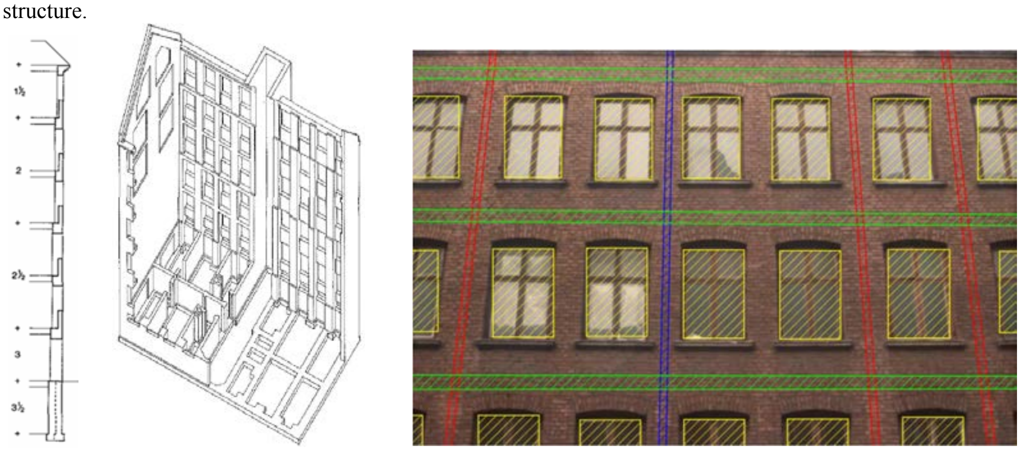
2. The traditional Danish multi-story housing, year 1850-1930

The first "modern" building code in Denmark took effect in 1856. This collection of regulations was groundbreaking, due to clear formulations covering construction details and choice of materials. At the same time, the code was thought through in such a manner that the general dimensions and construction techniques did not change until the 1930's, where a new building code was passed and materials such as concrete and steel became commonly used [8]. Initially, the building legislation applied to constructions in Copenhagen, but was quickly adapted to the regional boroughs of Denmark. The consequence of this strict building legislation is that buildings from the period 1850-1950 are generally built after the same principles, but gradually changing to more modern building methods through the last 20 years of the period.

One important parameter, which was defined in the building code, is the composition of the façade, including thickness of load bearing wall columns and dimensions of infill walls under the windows. The thickness of the wall columns varies through the building and is defined as shown in Fig. 1(a), with 1½ bricks at the highest floor and increasing downwards as illustrated in the figure. Windows are situated between the wall columns, and infill walls fill the façade in the areas between the windows and the floor decks, as illustrated in Fig. 1(b). The infill walls are of special interest, since they are always 1 brick thick regardless of the floor number, and thus constitute the thinnest part of the façade. The wall above the window has a thickness corresponding to the column size at the given floor. The building code further stated a maximum permissible degree of penetration of the facades to be 2/3 in the horizontal direction and 1/2 in the vertical direction. This maximum allowance resulted in very perforated facades, as illustrated in Fig. 1(b) & Fig. 1(c).

Fig. 1(b) shows the outer leaf of a typical construction from the relevant time period, with the maximum allowed penetration degree and minimum size of column and infill wall. This high degree of penetration is typical for the period. The figure clearly indicates the high complexity in geometry of the typical building, and that 1-dimensional condition for assessment of heat transmission though the walls are rarely present in practice. The only place where large undisturbed wall areas are present is in the gables, but these are generally built together with the next building and the heat loss of the gable wall is thereby negligible.

A figure showing a typical exterior surface of a construction from the relevant period is shown in Fig. 1(c). Hatches are included in the figure to indicate areas where interior insulation is not applicable. The yellow hatches mark windows, the red hatches show the position of solid interior walls for division of fire cells to neighboring apartments/staircases, the blue hatch show the position of interior walls which could be either timber or solid masonry walls, the green hatch indicate the position of the floor structure.



(a) (b) (c)

Fig. 1 (a) Thickness of wall columns in bricks. [9] (b) Maximum penetration of outer leaf. [9] (c) Exterior view of building (original photo by J. Engelmark).

3. Method for investigation

The investigation of possibilities for application of interior insulation will be split into two parts. First, the amount of relevant buildings and apartments are added up through a major database managed by the Danish Government. Next, the possible areas for application of interior insulation in the single apartments are determined through knowledge about the construction legislation that was in force at the time of construction.

3.1. Investigation of segment size through The Building and Dwelling Register (Danish abbreviation BBR)

The BBR register is a national register, administrated at a governmental/ministry level, which contains information regarding all buildings in Denmark [10]. The register was established in 1977 based on questionnaires to all owners, but has continuously been updated and extended so it now includes data regarding physical properties of the units, usage, rent, building services and more. The data is used by all levels of authorities and private companies, including banks and utility companies. This wide usage of the register and the extensive feedback and contributions it gets from the many users is assumed to keep a minimum the risk of possible errors in the database.

In the present article, the register is used to investigate the segment size of relevant multi-story dwellings in Denmark, where interior insulation could be a mean to enhance occupant comfort and reduce energy consumption.

3.2. Theoretical heat flux models, based on Danish construction legislation

As presented in Section 2, the buildings constructed in the period 1850-1930 have the same general composition, defined by strict legislation. The general working procedure in the period was architects dimensioning the multi-story buildings, generally to the limit of rules/codes, which were stated in short handbooks. Engineers were rarely involved in standard multi-story building, only if special details were needed. Due to this form of work, most of the buildings in the period were constructed with the same general characteristics. The building style of the Danish multi-story buildings has been extensively researched by J. Engelmark [8,9], resulting in extensive documentation about the composition of this type of buildings.

A range of different 1-, 2- and 3-dimensional models that represent the characteristic geometry of the segment illustrated in Fig. 1(b) & Fig. 1(c) are set up in the simulation software COMSOL Multiphysics [11]. The models are used to calculate the theoretical heat loss reduction, which can be achieved by applying varying degrees and thickness of interior insulation to characteristic details of the front/back facades.

The models are constructed with symmetry lines through the wall columns, and consist of the following:

- 1-dimensional model through the 1 brick infill wall.
- 2-dimensional model between two half wall columns.
  - The model has a width of 1.8m.
- 3-dimensional model between two half wall columns and upper/lower part of floor deck structure with a window.
  - The model has an exterior wall surface area of 2.70m^2, after subtracting the window area.
  - The window has a height of 1.12m and a width of 1.2m.

1-, 2- and 3-dimensional models are abbreviated as “1d”, “2d” and “3d” in graphs and caption text.

Insulation is applied in the different models as being either partly insulated, where only the infill wall below the window is insulated as illustrated in Fig. 2(a) & Fig. 2(c), or a full insulation which covers the entire interior surface, as illustrated in Fig. 2(b).

The models with different insulation degrees will be abbreviated in graphs and caption text as “partly” for models with only partly covering infill insulation, and “fully” for models with insulation covering the entire interior surface.

The thermal conductivity of the materials in the model are mainly obtained from the Delphin material database [12] as:

- Masonry (brick + mortar), λ=0.8 W/m/K.
- Thermal insulation, λ=0.045 W/m/K.
- Wood, λ=0.194 W/m/K.
- Sandy clay, used in the pugging, λ=1.76 W/m/K.

The properties of air are built-in in COMSOL Multiphysics [11]. The heat transfer through the air is thereby not limited to conductivity, but also includes radiation and convection depending on the dimensions of the object.

The heat flux through the window is subtracted from the total heat flux of the model, making the U-value unimportant.

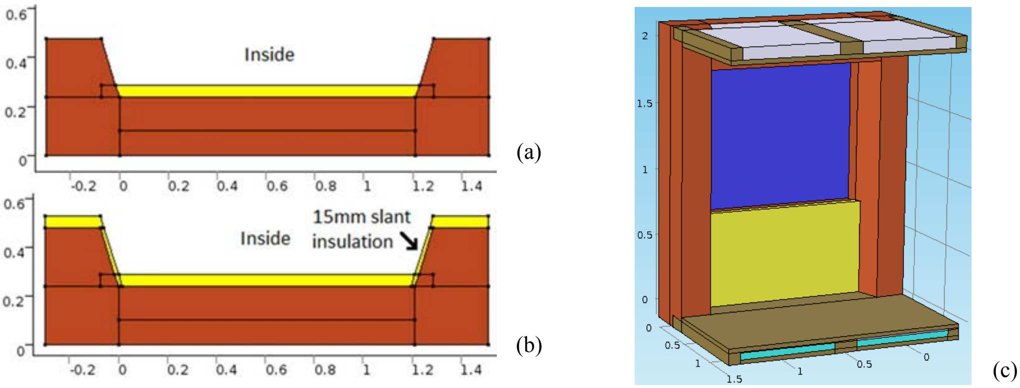


Fig. 2 Examples of used models. (a) 2d, partly insulation of infill wall. (b) 2d, fully insulation. (c) 3d, partly insulation of infill wall.

In the 2- and 3-dimensional models for walls that are fully covered with insulation, a slanted insulation board with a thickness of 15 mm is used at the sides of the column and around the window, illustrated in Fig. 2(b). In the model with 10 mm insulation, this slanted insulation is only 10 mm as well. The models in this article are based on a wall column depth of 2 bricks, corresponding to the traditional construction at the second and third floor from the top.

4. Results

4.1. Segment analysis through the BBR

The BBR database is used to evaluate the amount of multi-story buildings which exist in Denmark. The distribution of multi-story apartments, sorted after building period and stories in the buildings, are evaluated in Table 1. The building periods are inspired by Wittchen & Engelmark [2,8] and represent shifts in building style.

As it can be seen in Table 1, a large proportion of the Danish multi-story buildings originate from the period 1850-1950. This period further represents large heat consumption, as the buildings were constructed without considerations of thermal insulation. The constructions thereby have a large potential for energy saving [1-3]. The last part of the period, 1930-1950, differs slightly from the first part with a beginning use of cavity walls and concrete structures, but geometries generally follow the same principles as the earlier period.

The data in Table 1 are limited, so only apartments situated in buildings higher than 2 real stories are included, to exclude minor 2-story town houses split vertically between 2 households. Used basement and attic space is not included in the definition of the number of stories.

4.2. Investigation of heat flux through simulation

The calculated average U-value and corresponding reductions from simulation of the different models presented in Section 3.2 are illustrated in Fig. 3. The specific heat flux through the window is subtracted from the total heat flux through the exterior façade, and the resulting specific heat flux for the wall is divided by the wall area of the construction to obtain the average U-values of the walls.

The reductions are defined as the difference between the average U-value of the original un-insulated model, compared to the average U-value of the insulated models with increasing insulation thickness.

Table 1 Segment analysis, number of multi-story buildings and apartments. Data drawn on 2014.03.28

Sorting criteria		3 stories	4 stories	5 stories	6+ stories	Sum
Multi-story dwelling, brick façade, 1851-1930	Buildings	5883	2966	5348	635	14832
	Apartments	47559	37636	115284	18723	219202
Multi-story dwelling, brick façade, 1931-1950	Buildings	4148	1114	1408	168	6838
	Apartments	81604	25470	52289	10436	169799
All multi-story dwellings in Denmark	Buildings	18614	7372	7927	1857	35770
	Apartments	335533	176357	212901	105452	830243

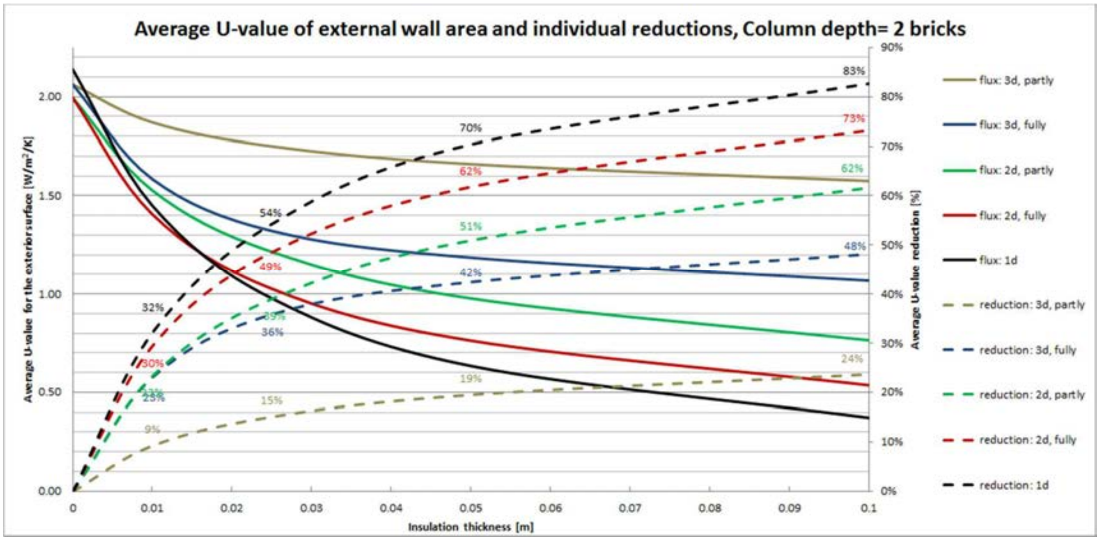


Fig. 3 Average U-value for exterior wall area. Insulation thickness: 10, 25, 50 & 100 mm. Fully = fully insulated facade, partly = insulation only of infill wall.

5. Discussion

5.1. Size of segment

As presented in Section 4.1, the segment of buildings in Denmark with brick facades from the period 1851-1930 is very large, with 219,202 apartment units distributed over 14,832 unique buildings. This segment is based on the same construction methods, with minor alterations, which makes general strategies for application of insulation possible for a large number of apartments/buildings. The buildings from the latter period 1931-1950 with brick facades are further shown in Table 1 with 169,799 apartments distributed over 6,838 unique buildings. The shared building style does however indicate that energy refurbishment strategies for the 1850-1930 period buildings can be used to some extent also in buildings from the 1930-1950 period, to increase occupant comfort and decrease energy consumption.

The large segment of buildings from the periods 1850-1930 and 1930-1950 makes it possible to develop a series of methods proven to work for the building style under different boundary conditions, such as orientation, wind-driven-rain load, material properties and the condition/wear and tear of the building, including consideration of possible cracks in the façade.

5.2. Energy saving potential in simulated fields between two columns

The developed COMSOL models in Section 4.2 are used to evaluate the resulting average U-value and corresponding U-value reduction when applying different degrees of insulation. The results from these models are illustrated in Fig. 3. A 1-dimensional model, illustrating the theoretical heat loss reduction of the thin infill wall, is shown as a reference. As mentioned in Section 2, 1-dimensional heat flux is not reasonable to assume for the facade, due to the many construction details of the old buildings.

The 2- and 3-dimensional models are evaluated based on two different insulation strategies, presented in section 3.2 and illustrated in Fig. 2(a), Fig. 2(b) and Fig. 2(c). The results of the simulations in Fig. 3 show an energy saving potential for the wall part of the façade of up to 48% by the application of 100 mm interior insulation. It is seen that the 2-dimensional models in general overestimate the reduction in average U-value in both insulation strategies, compared to the more detailed 3-dimensional model. It can further be seen that the 2-dimensional models only yield a minor difference between partly and fully covering of the interior surface, with an additional approximately 20-26% reduction by full application of insulation, as illustrated in Table 2. The 3-dimensional models gives a significantly different picture, with a large difference between fully and partly covering insulation of the interior area. As illustrated in Table 2, this suggests that the heat flux reduction can be doubled, or more, by going from only insulating the infill wall, to fully covering the interior surface.

Table 2 Increase in heat flux reduction, from partly to fully covering insulation strategy

Insulation thickness	10 mm	25 mm	50 mm	100 mm
2d flux increase, from partly to fully insulation strategy	26 %	24 %	21 %	19 %
3d flux increase, from partly to fully insulation strategy	149 %	138 %	118 %	104 %

The large differences between the two insulation strategies occur due to the many extra details that are included when going from 2- to 3-dimensional simulation. Even though the heat flux through the window is excluded from the results, the heat flux imposed from the geometry of the wall around the window yields a significant increase. The declining reduction in average U-value with insulation thickness in Table 2 is believed to derive mainly from the maximum insulation thickness of 15 mm at the sides of the column wall. This maximum insulation thickness of 15 mm will result in a significant heat flux which cannot be avoided. The floor structure is not included in the 2-dimensional model as well. The floor structure is rarely opened and insulated when performing refurbishment of multi-story buildings in Denmark, which entail that there will be an uninsulated wall area between the floor and roof boards.

Based on the large difference and clear distinction between 2- and 3-dimensional results in Fig. 3 and Table 2, it can further be concluded that 3-dimensional analysis is needed to obtain realistic results.

6. Conclusion

The investigation performed in the present article shows a large segment of multi-story buildings with brick façades in Denmark from the period 1851-1930. The 219,202 apartment units distributed over 14,832 unique buildings are all constructed based on the same strict legislation, with resulting similar geometries. The large segment and big similarity provide an argument that general solutions towards reducing energy consumption could be thoroughly developed to streamline the future process of retrofitting the buildings. The facade wall part of the buildings has been shown to contain an energy saving potential of up to 48% with 100 mm insulation. There is some potential for energy saving by applying insulation to the infill wall beneath the windows in the façade, but a 100-150% larger saving can be obtained by performing a fully covering interior insulation. Based on the large difference and clear distinction between 2- and 3-dimensional results in Fig. 3, it can further be concluded that 3-dimensional analysis is needed to obtain realistic results.

It should be noted that the present investigation is purely based on heat flux; further investigation/development is needed to ensure occupant comfort from cold surfaces and hygrothermal safety in design of interior insulation strategies.

The retrofitting of insulation to the entire interior surface has previously shown to be a large and complex operation, with high cost involved, as the fitting of insulation needs to be thorough to limit the introduction of thermal bridges and reposition of technical installations and wooden panels. Due to the large similarity between buildings from the relevant period, combined with the large size of the segment, this could be an argument for the development of thorough solutions, which could bring down the uncertainty and streamline the process of retrofitting insulation to the building segment.

Acknowledgements

Many talks with Jesper Engelmark, concerning the building style and details of Danish multi-story buildings from 1850-1950, are greatly acknowledged.

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