Development of a facade system containing slotted steel girders – hygrothermal aspects

Belső acélvázas homlokszati rendszer fejlesztése – hő- és páratechnikai aspektusok

Theses of the dissertation

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1. Introduction

1.1. The choice of the subject

All the sectors of the world economy have occasionally notable harmful effect on its environment. The increasing speed of development of different sectors puts forward the necessity of protecting the environment. This plays a minor role in the case of creating buildings, also. On the one hand the environment friendly methods and on the other hand the use of building materials, methods and systems with advantageous thermal properties are spreading at the development of the building construction methods and planning, also.

There are lightweight building methods coming from the United States of America and Northern Europe spreading all over the World and also in Hungary that are in accordance with these requirements.

Lightweight building method is built with different materials. The load bearing framework is usually from wood or steel. This building method is used for one or two storeys high domestic houses, as infill or curtain walls of reinforced concrete skeleton frame buildings, or in special cases as additional floor at reconstruction.

The Hungarian production of a special steel girder with slotted web used for lightweight buildings and facades adapted from Sweden was started in the fall of 2006. The slotted girders are used to decrease the thermal bridges caused by the steel girders in the facade. The slots cut into the web of the girder perpendicular to the way of the heat flow increases the path of the heat, because it has to go round the slots. However, it is a question, if with this solution a major decrease in the thermal transmittance value of the wall can be achieved compared to the constructions containing steel girders with solid web. Another question is, if the geometry (slot length, width, distance from each other, thickness of steel) has an effect on the thermal efficiency.

Many girder constructions are produced in Sweden with the variables of the slot geometry, thickness of the steel, web height and flange width. There are U and C shaped girders with several steel thicknesses, web heights and flange widths are produced also in Hungary.

The Hungarian and Swedish building physics regulations and so the planning differs from each other. The basic differences are caused by the climatic environment. At the Southern part of Sweden the summers are warm but short, the winters are cold. Moving North there are areas which are covered with snow all year long. The average temperature is much lower than in Hungary. Further difference is the location of the Swedish cities, they are mainly close to seas.

The climatic conditions are totally differ from the temperature, vapour content and yearly precipitation of the Hungarian continental climate point of view. These differences can be found in the national building physics regulations, also. At the building physics calculations
of buildings different values have to be taken into account, which affect the constructions and utilities, also. Based on this, the slotted steel girder has to be analysed with the methods usable in the Hungarian circumstances.

Previously a small slice of this subject was already analysed by the author as Scientific Student Study and Diploma study. Those researches raised further questions, so the challenge was undertaken to make a more complex analysis of the subject. During the PhD researches due to the order of magnitude of the subject, only with a separate part of the subject was dealt with. Hygrothermal researches for this facade system were made and analysed, especially the use as infill and curtain walls of reinforced concrete skeleton frame buildings. There are detailed calculations about the thermal effect of the slots in the web of the steel girders, the possibilities of different special slot geometries and the optimization of the layer orders of the facade system.

From 2008, during the researches some buildings were constructed using this building system in Hungary. The thermovision monitoring of these buildings where the control of the results coming from the computational simulations.

The subject in Hungary is topical, because this building system containing slotted steel girders can be used at newly built constructions and at reconstructions, also. Besides the favourable thermal properties further advantage of this system is the fast construction time, which is an important question e.g. in crowded downtown and center areas of big cities [Váradi 2007].

The hygrothermal behaviour of the facade where analysed in the dissertation within the subject of building physics. The result found in the dissertation are usable among others at the building energetics calculation for buildings corresponding to the regulation 7/2006. (V.24.), TNM About the calculations of the certificate of building energetics calculation, because in the literature there are mainly information about the wooden framed facades and there are only a few information about steel frames. The standards are not usable in all the cases when calculating steel framed facades. It is a further problem, that the softwares used for the certification can take into account the properties of the lightweight building methods only limited. These calculations give usable results and construction solutions for the use of facade with slotted steel girders.

1.2. The goal of the dissertation

The goal of the dissertation is the calculation of the hygrothermal behaviour of the facade containing slotted steel girders, the analysis of the history of the international development and the realized examples, the possibility of use in Hungary and the computational simulation of the different constructional facade solutions, on-site thermovision measurements, evaluation of results and based on these to give constructional proposals.
In this dissertation the hygrothermal behaviour of the facade was calculated. The information found in the literature are mainly about the subject of the stability of slotted steel girders and not about the building physics properties. There are also only a few results made with multidimensional calculations (e.g. analysis of whole parts of facades), and these results are often only approximations and cannot be used for the planning and designing of buildings.

During the researches the following goals were formulated, and the answers for the following questions were searched for:

a) Is it possible to use an equivalent thermal conductivity value of a solid web for the slotted web of the steel element?

b) Can this equivalent value be used in the complex computational models (which would increase calculation time and model size so the simulated part of a building could be larger? If this equivalent value can be used, than this value should be calculated for the developed slot geometries, also.

c) What is the thermal effect of the slotted steel girder in the facade used in Hungary?

d) The calculation of the facade layers and the search for the optimum solution. Are the calculated thermal transmittance values under the required limit given in the Hungarian regulations? Give solutions for the facade construction.

e) The applicability of the simplified method of calculating the thermal resistance of the facade. How this regulation and calculation method can be used in the case of using slotted steel girders in the facade?

f) The analysis of vapour conductance of the facade system containing slotted steel girders.

The results found in the dissertation are generally valid, the initial and boundary conditions used for the calculations were taken from standards and the literature of the subject.

2. Research methods and assumptions

Computational simulations were made to analyse the thermal behaviour of the slotted steel girder and different facade sections. As first step the slotted web of the steel girder was calculated. As second step the hygrothermal properties of the facade layers were analysed. The calculations were checked with the results coming from thermovision measurements.

2.1. The construction of the building system

The analysed facade system is made with lightweight building method and can be used as infill or curtain walls of reinforced concrete skeleton frame buildings, or as additional floors. It can be used at newly constructed buildings and at reconstruction, also. The load bearing elements of the facade are the U and C girders with slotted web. Inside the framework there is
infill insulation. The slotted girders are used with 120, 150 and 200 mm web height, and with 1,0; 1,2 és 1,5 mm steel thicknesses.

![Figure 1. The lightweight facade system used as infill walls (see Dissertation Figure 5.4.).](image)

On the internal and external side of the steel frame gypsum board or other plating materials have to be placed. The additional layers are placed on these basic layers. As external layers insulation with plastered cladding, brick cover with ventilated air layer or wallcassette cladding can be placed.

![Figure 2. The facade with plastered cladding (see Dissertation Figure 3.4.).](image)

On the internal side airgap for mechanical fittings and additional gypsum board layers can be placed. Concerning the air and vapour tightness, different foils should be used.

### 2.2. Computational simulation, hand calculation and thermovision monitoring

Computational simulations were made to analyse the thermal behaviour of the slotted steel girder and whole facade sections. As first step the slotted web of the steel girder was calculated. As second step the hygrothermal properties of the facade layers were analysed. The thermal transmittance value of the facade can be calculated based on the standard MSZ...
EN 6946 Building components and building elements. Thermal resistance and thermal transmittance. Calculation method, the vapour conduction was calculated based on the standard MSZ EN ISO 13788 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods. The simulations of the heat conduction behaviour of the slotted web were carried out with the finite element programme ANSYS (version 11.0), the hygrothermal behaviour of the facade was calculated with the programmes HEAT3 5.0 and WALLAnalyzer 2.0.

The calculations were made in the following steps:

a) the thermal transmittance value calculation of the slotted web, development directions;

b) the thermal calculation of the facade layers with computational simulations and hand calculations, checked with thermovision measurements;

c) calculation of the vapour conduction of the facade layers: possibility of internal surface and interstitial condensation.

Three newly built Hungarian office buildings were measured with thermovision to check the validity of the computational simulation and the quality of the building construction. These measurements gave information about the internal and external surface temperatures. Based on these data the computational simulations could be validated.

3. The theses of the dissertation

The new scientific results are written in bold, the short explanations are written with normal characters. The numbers of the referring publications can be seen in square brackets.

During the thermal analyses of facades and different thermal bridges, in many cases it is a problem, that multidimensional numerical modell and a high number of finite elements are needed, so the calculation time and the expenses increase, also. To solve this problem it is recommended to use an equivalent thermal conductivity for the slotted webs in the complex numerical modells.

Thesis 1.

Based on numerical calculation I proved, that it is possible to give an equivalent thermal conductivity for the slotted web and to use it in further, complex modells. The simulations led to the same results in the case of using the slotted web or a solid web with the equivalent thermal conductivity, also. [3] (see Dissertation page 63.)
The perforation geometry patterns can be seen in Figure 3.: 

![Figure 3. The basic parameters of the slotted web (see Dissertation Figure 7.1.).](image)

One of the calculated cross sections of the facade can be seen in Figure 4.: 

![Figure 4. Cross section of the calculated wall sections (see Dissertation Figure 7.9.).](image)
Some of the results from the computational simulations, and the difference between them can be seen in Table 1. (n – number of perforation rows):

Table 1. Some comparison for using the equivalent thermal conductivity of the slotted web (see Dissertation Table 7.4.)

<table>
<thead>
<tr>
<th>web height</th>
<th>perforation pattern geometry</th>
<th>( \lambda_{eq} ) [W/mK]</th>
<th>( q_{slotted} ) [W/m²]</th>
<th>( q_{eq} ) [W/m²]</th>
<th>difference (between ( q_{slotted} ) and ( q_{eq} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 mm</td>
<td>( n=6, l=25, p=3, d=75, s=9 )</td>
<td>11,00</td>
<td>0,1726</td>
<td>0,1726</td>
<td>0,00 %</td>
</tr>
<tr>
<td>150 mm</td>
<td>( n=6, l=25, p=3, d=75, s=9 )</td>
<td>8,20</td>
<td>0,1996</td>
<td>0,1996</td>
<td>0,00 %</td>
</tr>
<tr>
<td>100 mm</td>
<td>( n=2, l=25, p=3, d=85, s=8 )</td>
<td>9,77</td>
<td>0,2641</td>
<td>0,2628</td>
<td>0,50 %</td>
</tr>
</tbody>
</table>

Thesis 2.

Based on numerical thermal simulations and thermovision measurements I proved, that the facades containing slotted steel girders with the web height 120, 150 and 200 mm produced in Hungary, the thermal performance regulations given in Hungary can be satisfied. The results of the numerical simulations were proved with the thermovision measurements. [2], [6], [8], [10] (see Dissertation page 71.)

Some of the calculation results of the thermal transmittance value can be seen in Table 2. The constructions which can be made from this facade system satisfies the thermal regulations of nowadays, and also the forcoming more strict values. In Table 2, there are two results for the same facade construction: once containing slotted, then solid steel girder.

Table 2. Some of the calculation results of the different layer constructions (see Dissertation Appendix 2.)

<table>
<thead>
<tr>
<th>web height</th>
<th>steel thickness</th>
<th>infill insulation</th>
<th>external insulation</th>
<th>( U_{slotted} ) [W/m²K]</th>
<th>( U_{solid} ) [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 mm</td>
<td>1 mm</td>
<td>120 mm</td>
<td>50 mm</td>
<td>0,22</td>
<td>0,27</td>
</tr>
<tr>
<td>150 mm</td>
<td>1 mm</td>
<td>150 mm</td>
<td>50 mm</td>
<td>0,20</td>
<td>0,25</td>
</tr>
<tr>
<td>200 mm</td>
<td>1 mm</td>
<td>200 mm</td>
<td>50 mm</td>
<td>0,17</td>
<td>0,22</td>
</tr>
</tbody>
</table>
The external continual insulation decreases the heat loss of the thermal bridges caused by the steel elements in a high degree.

**Thesis 3.**

Maximum 120 mm additional external insulation thickness shall be used at a facade containing slotted steel girders with the web height 120, 150 or 200 mm, with the distance 600 mm between them. Thicker insulation layer does not decrease notably the thermal transmittance value of the facade with slotted steel girders. In the case of using steel girder with solid web, up to further 50 mm additional insulation is needed to achieve the same result as with slotted steel girders. [6] (see Dissertation page 71.)

The calculation steps were taken to 10 mm, from the case when there is no external insulation until the thickness of 160 mm as it is seen in Figure 5:

![Figure 5](image)

*Figure 5. The thickness of the additional insulation (from 0 mm to 160 mm). (see Dissertation Figure 8.6.)*

The results of the calculations in the case of using slotted and solid girders can be seen in Figure 6:

![Figure 6](image)

*Figure 6. The effect of the thickness of the additional insulation on the thermal transmittance in the case of 120 mm web height (from 0 mm to 160 mm). (see Dissertation Figure 8.7.)*
The increase of running meter per square meter slotted steel girder in the facade, the thermal transmittance value of the facade becomes worse.

**Thesis 4.**

Based on computational simulations I proved that an average of 20 mm external insulation thickness is needed to compensate the duplication in the running meter length of the slotted steel girders. The increase of the thermal transmittance as the running meter of the steel girders per square meter the intensity of the increase will be higher, when using solid, than in the case of using slotted webs. The change is linear, between the limits of the amount of running meters used in a square meter, for both the solid and the slotted webs. The gradient fractions of the regression lines change with the function of the additional external insulation thickness. The highest difference is in the case when the external insulation thickness is zero. In this case the gradient of the line for solid webs will be the double of the gradient for the slotted webs. [6] (see Dissertation page 71.)

The calculated facade constructions can be seen in Figure 7:

As the running meter/m² facade increases, the thermal transmittance will increase, but it can be seen, the increase will be again less in the case of slotted steel girders, than in the case of girders with solid webs:

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![Figure 7. The increasing running meter/m² facade](image)

*Figure 7. The increasing running meter/m² facade (see Dissertation Figure 8.11.)*

![Figure 8. The effect of the increasing running meter/m² facade](image)

*Figure 8. The effect of the increasing running meter/m² facade (in the case for 120 mm webheight). (see Dissertation Figure 8.12.)*
Thesis 5.
Based on hand calculations and computational simulations I analysed the applicability of the simplified method for calculating thermal resistance and thermal transmittance value given in the standards and in the literature. These calculation methods give satisfying results in some cases, when the weighting factor given in the standard MSZ-04-140-2:1985 is used. However, my proposal is that with the weighting factor $p=0.2$, and as the running meter per square meter slotted steel length exceeds three meters, at the use of the weighting factor $p=0.1$ more accurate results occur. [7]

The geometry used for the calculation with simplified method can be seen in Figure 9:

![Figure 9. The geometry of the facade in the example for calculating the thermal resistance with simplified method (see Dissertation Figure 8.14.)](image)

In the case of 0-3 running meter/square meter steel quantity using $p=0.2$, otherwise $p=0.1$ weighting factor, the results of the computational simulations and the simplified method can be seen in Figure 10. (total coincidence is at the line with $45^\circ$):

![Figure 10. The difference between the results coming from numerical calculations and the simplified method given in the standards ($p = 0.2$ between 0 and 3 running meter per square meter slotted girder, $p = 0.1$ otherwise). (see Dissertation Figure 8.18.)](image)
Development of a facade system containing slotted steel girders

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With computational simulations together with hand calculations based on thermovision measurements I determined that at an average cross section the temperature of the internal surface of the facade will be $f_{Rsi} = 0,98$, at joints (windows, corners) it will be $f_{Rsi} = [0,76, \ldots, 0,90]$. I proved that at a functional internal air status, there won’t be surface condensation even at the surroundings of the joints. Because of the use of vapour barrier foil in the internal parts of the facade layers, there won’t be interstitial condensation inside the facade. [1], [6], [8], [11] (see Dissertation page 86.)

![Thermovision picture of the internal surface of the facade](image)

**Figure 11.** The thermovision picture of the internal surface of the facade (see Dissertation Figure 9.5.)

The surface temperatures along Li1 and Li2 (see Figure 11.):

![Internal surface temperatures](image)

**Figure 12.** The internal surface temperatures along Li1 and Li2 (see Dissertation Figure 9.6.)

It can be seen that there is approximately 1 °C temperature decrease along the slotted girder, and about 2.5 °C temperature decrease in the corner. The effect of the slotted steel girders together with the geometrical thermal bridge of the corner:

\[
f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} = \frac{21,1-3,9}{23-3,9} = 0,90 \geq 0,70
\]
4. The theses of the dissertation in Hungarian – Az értekezés tézisei magyarul

tézis értékű megállapítások kiemelten, valamint azok rövid magyarázatai normál betűtípussal szerepelnek, a szögletes zárójelben megadott számok a vonatkozó publikációt adják meg.

Homlokzati rétegrendi hőtechnikai vizsgálatok során, illetve különböző hőhidak vizsgálatánál számos esetben probléma a többszövetéses numerikus modell, valamint a nagy elemes számítások szükségessége, ezáltal a számítás időigényessége, illetve költségessége. Ezen problémák kiküszöbölésére javasolt a falszerkezetek összetett numerikus modelljeiben az egyenértékű hővezetési tényező alkalmazása.

1. tézis
A számítógépes szimulációk azonos eredményre vezetnek perforált gerinc, illetve az egyenértékű hővezetési tényezőt tőmör gerinc alkalmazása esetén is, ezáltal kimutattam, hogy lehetséges a perforált gerincere egyenértékű hővezetési tényezőt megadni, és a további, összetett falszerkezeti modellekből ezt a tényezőt alkalmazni. [3]

2. tézis
A számítógépes hőtechnikai szimulációk és az azokat követő termovíziós mérések alapján kimutattam, hogy a Magyarországon gyártott 120, 150 és 200 mm gerincmagasságú perforált acél szerkezeti elem tartalmazó homlokzati rendszer alkalmazásával a Magyarországon előírt hőtechnikai követelmények kielégíthetőek. A számítógépes szimulációk eredményeit termovíziós felvételek készítésével és kiértékelésével is igazoltam. [2], [6], [8], [10]

A külső oldali, folytonos hőszigetelés jelentős mértékben csökkenti az acélvázas szerkezet hőhidjaiból adódó energiaveszteséget.

3. tézis
Számítógépes szimulációval kimutattam, hogy a 600 mm-es osztásközö nként 120, 150 valamint 200 mm gerincmagasságú perforált szerkezeti elem tartalmazó falszerkeztnél legfeljebb 120 mm vastag külső kiegészítő hőszigetelést célszerű alkalmazni. Ennél vastagább hőszigetelés már nem csökkenti jelentős mértékben az acélvázas homlokzat hőátbocsátási tényezőjének értékét. Tömör acél szerkezeti elem alkalmazása esetén átlagosan akár 50 mm-rel vastagabb külső kiegészítő hőszigetelés szükséges a perforált szerkezeti elemet tartalmazó falszerkezet hőátbocsátási tényezőjével megegyező érték eléréséhez. [6]
A falszerkezet egy négyzetméterén belül található perforált szerkezeti elemek folyóméterhosszának növekedésével a falszerkezet hőátbocsátási tényezője romlik.

4. tézis
Számítógépes szimulációval kimutattam, hogy körülbélül 20 mm külső kiegészítő hőszigetelés vastagság alkalmazásával a falszerkezet egy négyzetméterében található elemek összes folyóméterhosszának kétzeresére növelése által a hőátbocsátási tényező értékében mutatkozik romlás ellensúlyozható.

Tömör szerkezeti elem alkalmazása esetén a hőátbocsátási tényező kedvezőtlen változása a folyóméter növekedésével fokozottan jelentkezik, mint perforált szerkezeti elem alkalmazása esetén. A változás – a gyakorlatban alkalmazott szerkezeti elem folyóméterhosszának keretein belül – tömör és perforált gerinc esetén is lineáris, a regressziós egyenesek meredekségének hányadosa a külső kiegészítő hőszigetelés vastagságának függvényében változik. A legnagyobb eltérés abban az esetben keletkezik, amikor nem alkalmazunk külső kiegészítő hőszigetelést. Ekkor tömör gerinc esetén az egyenes meredeksége közel kétzeresre a perforált gerincéhez egyenesének. [6]

5. tézis
Kézi számítás, valamint számítógépes szimuláció alapján megvizsgáltam a szabványokban és a szakirodalomban található, a hőátbocsátási ellenállásra, valamint a hőátbocsátási tényezőre vonatkozó egyszerűsített számítás alkalmazhatóságának lehetőségét. Ezen számítás bizonyos rétegrendi kialakítások esetén kielégítően pontos eredményt ad, ha az MSZ-04-140-2:1985 szabvány szerinti súlyozást vesszük figyelembe. Azonban javaslatom szerint perforált szerkezeti elemet tartalmazó homlokzat esetén pontosabb eredmény érhető el p=0,2, illetve ha a négyzetméterenkénti folyóméter meghaladja a három métert, p=0,1 súlyozás alkalmazásával. [7]

6. tézis
Számítógépes szimulációval, valamint termovíziós méréseken alapuló kézi számítással megállapítottam, hogy a homlokzati rendszer belső oldalán a felületi sajátléptékben mért hőmérséklet értéke egy általános falkeresztmetszet esetén $f_{Ra}=0,98$, csomópontok esetén (nyílászárók, falsarok) $f_{Ra}\in[0,76, \ldots, 0,90]$ között adódnak. Bizonyítottam, hogy rendeltetésszerű belső légállapotok esetében a csomópontok környékén sem kell számolni a belső síkon felületi kondenzációval. Megfelelő rétegrendi kialakítás esetén a homlokzati szerkezet belső rétegeiben nem válthat kondenzáció. [1], [6], [8], [11]
5. Major publications in the topic of the dissertation

Chapter in a book

International journal paper

International conference papers

Hungarian conference papers
6. Utilization of results and further research questions

The results of the dissertation can be used as the supplements of the previous results found in the literature, to the development of the slotted steel girder from a thermal performance point of view, and to increase the quality of the Hungarian buildings. The results coming from the optimization of the facade layers and the recommendations can be used in the future planning of new buildings and at reconstructions, also.

As one of the further research questions, the development of the slotted steel element has to be mentioned. It has to be analysed, how does the better thermal performance effect the stability of the girders. It is possible, that the improvement in thermal properties will decrease the stability of the slotted steel element, so further researches are needed, where these two properties are measured together, in the same time, and with this method and optimum solution can be constructed. After this, the new perforation geometry and the properties have to be built in the softwares used by the constructors, so it would be available for the designers.

The already existing Hungarian buildings have to be monitored onwards, so further conclusion could be made with their help.