THESES OF THE DOCTORAL (PH.D.) DISSERTATION

RELIABILITY ANALYSIS OF WOODEN WINDOWS' PERFORMANCE CAPABILITY

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1. INTRODUCTION, OBJECTIVES OF THE RESEARCH WORK

In recent years, due to new technologies and more severe building energy directives the development of doors and windows structures have accelerated. In these developments most attention was paid to increase the heat transfer resistance of the structures. This can be explained by the fact that even in the case of new, modern doors and windows structures the heat transfer coefficient is higher than of buildings flanking walls made by modern construction technologies and using adequate materials. Researches related to the determination of hourly required air exchange volume reveals that filtration energy loss of a newly built in and well-fitting modern doors and windows is a fraction of the total building transmission energy loss and the filtration energy loss through building's other slots even at low external and internal pressure difference. Additionally, through these high sealed doors and windows the adequate fresh air supply for a good comfort feeling is not guaranteed. Due to the above mentioned reasons less research has been focused on the reliability analysis and increasing of windows air tightness performance. It is known that in the energy use of a building the custom of the persons living in that building, the electric power required by appliances and of course the insulation capacity of the building products plays an important role.

Several researches carried out in real conditions, pointed out that the actual power consumption may exceed the estimated consumption by close to 50%. The difference between the two values is due to people's diverse ventilation and heating habits, erected from different comfort needs and the calculated and real performance of construction products. Having this in mind, a survey has been started to control the state of windows after several years of use and determine the air tightness of these initially excellent performing windows. Result of the survey revealed that the initial air tightness of all windows dropped significantly which may contribute to the differences between designed and real energy loss of a building.

The main goal of my research work was to examine and describe the failure process of built-in wooden windows used in Hungary and the northern countries of the European Union as well as to increase the reliability of air tightness performance characteristics. In recent decades we experienced a continuous growth of installed plastic windows in contrast to wooden windows however due to the material properties differences and distinct structures the reliability test results of wood windows are just partially applicable on plastic windows.

From the set of twenty-three technical characteristics enumerated in standards this thesis deals only with the reliability of air tightness performance because of its very complex nature and interaction with other factors.

The ventilation of buildings is an important task to conserve the buildings in good conditions and assure a healthy environment of its people, but this air change it will only be effective if it does not take place in an uncontrolled manner, but in a precise and controlled one. To prevent the uncontrolled air exchange due to use of windows and other environmental influences is important both economically and in terms of comfort sensation. From the energetic point of view not necessarily the direct losses from the ventilation during the air exchange per hour means the greater surplus of energy; in fact, the uncontrolled cold air filtrated through the structure of slots substantially cold the surroundings resulting in local thermal bridge. Those colder areas and local air intakes greatly contribute to the development of local discomfort.

One aim of this paper is to explore and provide an accurate picture about what factors affect the air tightness performance of windows structural elements and reveal their significance. First step in increasing the reliability of air tightness performance of windows is to develop a model able to predict with a certain safety level the analyzed function parameter value in every moment during the product life cycle taking into account the input data available at design stage. In the interest of attaining this goal I defined first the air tightness performance changes due to the wear and tear of structural elements over time. The structural elements and other window components were artificially aged and tested at certain time intervals. Knowing the degradation process of the structural elements a reliability model has been built which take into account the rate of degradation effects from use and environmental exposures with a certain probability. Based on the simulation software implemented on the basis of reliability model the maintenance of the windows can be planned which lead to extend the product life time and reliability of air tightness performance

2. MATERIALS AND METHODS

The research is divided into four distinct stages. In the first and second steps a secondary research was carried out, while during the third and fourth stages of the work a reliability model was created able to predict the air tightness performance of the windows based on the first two steps results. To perform the on-site air tightness tests a special and unique equipment has been developed which measured the air tightness of the built in windows with the same precision than standard laboratory testing rig. Air tightness measurement of stored windows was carried out according to the EN 1026:2001 standard, the measurement results were evaluated according to EN 12207:2001 standard.

In the second research phase the effect of windows structural elements on air tightness performance capability was examined. During the research, a number of different sized and shaped windows with various sealings were measured as well as the effect of hinges settings. The influence of temperature as an environmental factor was analyzed at Non Profit Limited Liability Company for Quality Control and Innovation in Building (ÉMI) Laboratory.

In the third section, a model able to estimate the air tightness performance of a window was created based on the secondary research results. The model incorporates the relationship between gap geometry and air flow, the sealings' rheological behavior, the initial geometry of sealings, the variation of gap geometry influenced by wind load and tear and wear of hinges.

In the fourth stage the input data needed for the simulation model was measured on a chosen window and the numerical form of the model was determined. Due to the stochastic nature of the measured data the Monte Carlo simulation was used to get the model solution.

3. SUMMARY OF THE RESEARCH RESULTS

During the research extensive investigations were carried out on reliability modeling of air tightness performance of wooden windows.

In the first phase of the research work air tightness measurements on used windows were performed, the tests took place both in laboratory and on-site conditions. For on-site measurements a new testing equipment was developed capable to determine the air tightness performance of built-in windows. According to test results performed on safely stored windows after the initial type testing it was found that the air tightness performance decreases over time even in the case when the window is not exposed to repeated openings. Based on test results it was demonstrated that the flowing coefficient is changing by pressure increase, therefore the air tightness values determined by Blower Door test cannot be extrapolated to estimate the windows air tightness performance on high pressures.

The second stage of the research is dealing with the influence of structural elements on air tightness. design elements that affect the testing air tightness performance occurred. The wing doors During the examination of the impact of flexible gaskets several planes air tightness performance impact that the application of the secondary edge seal doors and windows does not improve the performance of air sealing and insulation capacity is below the center of the seal. Airtightness performance reliability of the use of the seal lip does not increase, it is not appropriate to apply air sealing point of view

The second stage of the research deals with analyzing the influence of structural elements on air tightness. In the case of elastic sealings placed at multiple places on a window sash it was determined that the secondary sealing does not improve the air tightness performance of windows and the insulation properties fall well behind the primary sealing's similar characteristic. The reliability of the air tightness performance is not increased by introducing a secondary sealing, therefore use of the secondary sealing from air tightness point of view is not justified.

The air tightness tests performed at different chamber temperatures (-10 ° C , -20 ° C , +23 ° C , +45 ° C) revealed that the ambient temperature affect significantly the windows air permeability only at 600 Pascal pressure difference.

During the rheological tests of the primary sealing the Burgers rheological material model was used to characterize numerically the stress relaxation process of thermoplastic elastomer materials. Determination of relaxation processes for sealings with complex geometries and different material compositions is almost impossible by standard material testing methods because of the multidimensional stress state developed in certain places of the sealing profile. Using the material characteristics determined by standard methods as input data a finite element model can be built as an accepted alternative to the present methods.

The most significant result of this research was the development of two numerical models capable to predict the air tightness performance of windows in function of stress level for the entire service life.

The first model has a limited use in estimating the airtightness. A second model which numerical form was established also and it is based on the first model gives a more precise estimation of the air tightness. The last model takes into account the gap closure index value at a pressure difference of 600 Pascal, the index indicating the sash and frame closure at the indicated is pressure. The adequate function describing the relationship between gap closure index and air permeability was determined by regression analysis of the measured data.

Because of the stochastic nature of input parameters a computer program was developed to predict the air tightness of a windows based on Monte-Carlo simulation method. The model algorithm was introduced on a sample window as well as the program functioning was demonstrated. Based on the air tightness simulation results it was established that the air leakage of the windows has a maximum asymptote in function of the opening-closing tear. The speed of performance drop is determined in small extent by the moving parts wearing and in large extent by the rheological properties of the sealings.

4. THESES

1. First step in increasing a technical product's reliability is to develop a model able to predict with a certain safety level the analyzed function parameter value in every moment during the product life cycle taking into account the input data available at design stage.

   The model able to predict the windows air tightness performance has the following numerical form:

   $$V(t) = \int_0^L \left[\beta_4 \cdot \left(1 - \exp(-1 \cdot \left((\beta_3 \cdot \Delta y_z(t) - 1 \cdot \beta_2)^{\beta_1}\right)\right)\right] dl$$

   Where:

   $\beta_1, \beta_2, \beta_3, \beta_4$ - function parameters

   $\Delta y_z(t)$ - the gap closing index at time t

   The stochastic nature of the variables from the model the use of the Monte Carlo simulation. Based on this model the developed simulation software assure a completely new tool to design the windows air tightness performance reliability considering the available input data during the product development.

2. During the research work an unique testing rig has been developed which makes possible the determination of air tightness performance of a window on site similar to standard laboratory measurements

   Using the individual measuring device developed throughout the research and the laboratory equipment I found that after 3-4 years of use the air tightness performance of the windows declines with a minimum of one class. At higher pressures the filtration heat flow exceeds the transmission heat flow due to the performance drop.

3. During the development of the air tightness predicting model a new index, the so called gap closing index. The newly introduced index expresses the capability of a windows

sealant to fill out the gap between sash and frame at a certain wind load. The index includes the rheology model of the sealant, the initial geometry, the wind load and the sash and frame gap varying in function of wear and tear effect. The gap closing index can be determined using the following formula:

$$\Delta y_z(t) = y_{töm}(t_0)\cdot\left[\left[\frac{y_{töm}(t_0)-y_{rés0Pa,z}}{y_{töm,z}(t_0)}\right]\cdot\left[\frac{\tau_{11}-T_2}{T_1-T_2}\cdot\exp\left(-\frac{t}{T_1}\right)+\frac{T_1-\tau_{11}}{T_1-T_2}\cdot\exp\left(-\frac{t}{T_2}\right)\right]\right]+$$

$$+\,y_{rés0Pa,z}-\left[y_{rés600Pa,z}(t_0)+\beta_1\cdot\left(\frac{t}{t+\beta_2}\right)\right]$$

Where:

τ_{11} és τ_{22} - time constants of the Burgers model

T_1 és T_2 - time constants of the Burgers model

t - usage time

β_1, β_2, - function parameters

$y_{töm(t0)}$ - height of the unloaded sealing at time t_0

$y_{rés0Pa,z}$ - distance between sash and frame measured at closing line z of the primary sealing at pressure 0 Pa

$y_{rés600Pa,z}$ - distance between sash and frame measured at closing line z of the primary sealing at pressure 600

4. Windows are exposed to abrasive stresses during their operation confirmed by measurements. The distance between sash and frame are varying due to the wear and tear at a measurable level. The functional relationship of operating cycles and sash displacement based on significant number of fatigue tests can be described by the following relationship:

$$f(x) = 0{,}91\cdot\left[\frac{x}{5884+x}\right]$$

Where:

x - the operating cycles

5. Amount of air penetrating trough the gaps between sash and frame was determined using an unique measuring chamber. The relationship among global air tightness of a window and unit gap length in function of the elastic sealant and frame surface distance has he following form:

$$g(x) = 110{,}96\cdot\left(1-\exp(-1\cdot\left((0{,}98\cdot x-0{,}42\right)^2\right)\right)$$

Where:

x- measurable distance between and frame

6. By using the simulation software developed on the base of reliability model it was determined that air tightness performance of a window with weekly cross-linked elastomer sealant mounted on it decreases asymptotically toward a minimum value in function of wear and tear of usage.

PUBLICATIONS RELATED TO THE TOPIC OF DISSERTATION

1. Tibor Szövérfi, **Balázs Bencsik**, Viktor Utassy, Levente Dénes: Air tightness on site analysis of built in windows, Proceedings of Brassó-Sopron Student Scientific Conference, PhD Volume, July 19, 2013 Sopron ,Hungary, Palatia Publisher, Győr, pp.81-95. (ISBN:978-963-359-023-2)
2. **Balázs Bencsik**, Zsolt Kovács, Tibor Szövérfi, Levente Dénes: Stress Relaxation of Elastic Sealing Used for Windows. 4th International Joint Conference on Environmental and Light Industry Technologies, November 20-22, 2013, Óbuda University, Budapest, Hungary
3. **Balázs Bencsik**, Tibor Szövérfi, Zsolt Kovács, Levente Dénes: The effect of sash and frame distance variation on windows air tightness capability. Proceedings of Brassó-Sopron Student Scientific Conference, PhD Volume, July 19, 2014 Sopron, Hungary, Palatia Publisher, Győr, pp.45-56. (ISBN:978-963-359-023-2)
4. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: The effect of windows air tightness performance decrease on the heat loss by filtration.
   FAIPAR LXI:(4) pp. 5-11. (2013)
5. **Balázs Bencsik**, Tibor Szövérfi, Levente Dénes: Intelligent Window Sealing with Improved Air Tightness. The Impact of Urbanization, Industrial and Agricultural Technologies on the Natural Environment: International Scientific Conference on Sustainable Development and Ecological Footprint. 400 p., March 26-27, 2012, Sopron, Hungary, National Textbook Publisher, University of West Hungary, pp.377-385 (ISBN: 978-963-19-7352-5)
6. **Balázs Bencsik**, Levente Dénes, Tibor Szövérfi: Gap Independent Window Sealing with High Air Tightness Performance, The Impact of Urbanization, Industrial and Agricultural Technologies on the Natural Environment: International Scientific Conference on Sustainable Development and Ecological Footprint. 400 p., March 26-27, 2012, Sopron, Hungary, National Textbook Publisher, University of West Hungary, eDOC (https://bismarck.nyme.hu/fileadmin/dokumentumok/palyazat/tamop421b/IntConference) (ISBN:978-963-19-7352-5)
7. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: Windows air tightness performance change in function of ambient temperature FAIPAR 60:(1) pp. 10-16. (2012)
8. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: The effect of windows structural elements on performance characteristics Part I. The effect of elastic sealings on windows air tightness. FAIPAR 59:(2-3) pp. 26-34. (2011)
9. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: The effect of climate temperature on windows air tightness performance characteristic. Proceedings of Brassó-Sopron Student Scientific Conference, July 19, 2011 Sopron ,Hungary, Palatia Publisher, Győr,. (ISBN:978-963-9883-79-6)
10. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: The effect of structural elements on windows performance characteristics: Part1. The influence of sealing's on air tightness

Proceedings of International Conference „Wood Science and Engineering" – ICWSE 2011, November 02-04, 2011, Brasov, Romania, pp. 467-473.

11. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: Sealings Influence on Windows Air Tightness Performance PRO LIGNO 7:(4) pp. 83-91. (2011)
12. **Balázs Bencsik**, Zsolt Kovács, Levente Dénes: Performance characteristics of windows in the course of their service life. Proceedings of 2nd International Joint Conference on Environmental and Light Industry Technologies, November 21-22, 2011 Óbuda University, Budapest, Hungary, p. CD. (ISBN:978-615-5018-23-7).