AIRTIGHTNESS OF WINDOWS: A MONTE CARLO SIMULATION MODEL

Levente Dénes, János Kalmár, Tibor Szövérfi, Balázs Bencsik

University of West Hungary

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Airtightness performance of windows

Why should we consider?

• Construction product regulations (CPR)

• Increasing heat insulation requirements

• Passive house certifications

• Heritage conservations

• Users’ comfort
Airtightness performance of windows

- Pressure differences between the two sides of a window occurs, because of the temperature and wind load differences
- Due to the pressure differences the filtration phenomenon will take place, affecting:
  - Indoor air quality
  - Comfort level of users
  - Energy consumption (heating, cooling, filtration)
- Performance measured by test rig
- Classification according to standards
Air tightness estimation model

The model estimates the air flow through the windows in function of gap geometry between sash and frame developed under certain pressure difference conditions.
The Gap Closure Index

The height change of sealings due to permanent deformations:

\[ y_{seal}(t_0) - y_{seal;z}(t_2) = \Delta y_{seal;z}(t_2) > 0 \]

**Gap Closure Index (\( \Delta y_z(t) \))**:
- characterizing the sealing capacity in one point \((z)\) of the closure line at a certain moment
- determined as the difference between gap \((y_{\text{gap}600\text{Pa};z}(t))\) and height of the sealing \((y_{\text{seal};z}(t))\) in unloaded conditions at 600 Pa

\[ \Delta y_z(t) = y_{seal;z}(t) - y_{\text{gap}600\text{Pa};z}(t) \]
Input data for the realiability model

- The initial height of primary sealing of a window \( y_{\text{seal}(t_0)} \)
- The stress relaxation function of the sealing which enable to determine the expected height of the sealing \( y_{\text{seal};z(t)} \) in unloaded state at any moment \( t>0 \)
- The expected distance between sash and frame along the perimeter at 0 Pa pressure \( y_{\text{gap0Pa};z} \)
- The expected distance between sash and frame along the perimeter at 600 Pa pressure \( y_{\text{gap600Pa};z} \)
- The function describing the relationship between Gap Closure Index and air tightness

\[ V(t) = f(\Delta y_z(t)) \]
The relationship between Gap Closure Index and air tightness

\[ g(\Delta y_z) = \beta_4 \cdot (1 - \exp(-1 \cdot (\beta_3 \cdot \Delta y_z - 1 \cdot \beta_2)^{\beta_1})) \]

where:
- \( g(\Delta y_z) \) – air leakage
- \( \Delta y_z \) – Gap Closure Index
- \( \beta_1, \beta_2, \beta_3, \beta_4 \) – parameters of the fitted function

The parameter values:
- \( \beta_1 = 2,00 \)
- \( \beta_2 = 0,421 \)
- \( \beta_3 = 0,887 \)
- \( \beta_4 = 110,961 \)

\( R^2 = 0,996 \)
Rheology of the sealing

Aim: to determine the height decrease of the sealing due to stress relaxation: $y_{seal;}(t)$

Rheology model of the thermoplastic elastomeric sealing: Burgers relaxation model with 4 parameters

Tests performed on heat treated samples at two different duration, number of samples 15 per treatment.
Sash and frame distance determination along the perimeter

Distances ($y_{gap0Pa;z}$) measured at 51 points using plasticine
Sash and frame distance determination along the perimeter

Aim: to determine the sash and frame gap at 600 Pascal windload and the distance variation in time due to hinges wearing \( (y_{gap 600Pa; z; t}) \).

The fitted function:

\[
 f(x) = \beta_1 \cdot \left[ \frac{x}{\beta_2 + x} \right]
\]

\( R^2 = 0.728 \)
Sash and frame distance variation along the windows life cycle

Transforming the gap increasing (wearing) function

Distinguished daily opening cycles:

Level 0: there is no opening
Level 1: 1 opening per day
Level 2: 2 openings per day
Level 3: 10 openings per day
The airtightness estimation model

Numerical form of the model

• Gap Closure Index value determination:

\[
\Delta y_z(t) = y_{\text{seal}}(t_0) \cdot \left[ \frac{y_{\text{seal}}(t_0) - y_{\text{gap0Pa},z}}{y_{\text{töm},z}(t_0)} \right] \cdot \left[ \frac{\tau_{11} - T_2}{T_1 - T_2} \cdot \exp\left( -\frac{t}{T_1} \right) + \frac{T_1 - \tau_{11}}{T_1 - T_2} \cdot \exp\left( -\frac{t}{T_2} \right) \right] +
\]

\[
+ y_{\text{gap0Pa},z} \cdot \left[ y_{\text{gap600Pa},z}(t_0) + \beta_1 \frac{t}{t + \beta_2} \right]
\]

• The air leakage along the windows farmers, in function of GCI value:

\[
V(t) = \int_{0}^{L} \left[ \beta_4 \cdot \left( 1 - \exp\left( -1 \cdot \left( (\beta_3 \cdot \Delta y_z(t) - \beta_2)^{\beta_1} \right) \right) \right] dl
\]
The airtightness estimation model

Stochastic parameters of the model:

- Change of the sealing’s material properties affects the relaxation process: 
  \( y_{\text{seal}, z(t)}:\mathcal{N}(\mu, \sigma) \)

- The initial height of the gap depends mainly on manufacturing conditions: 
  \( y_{\text{seal}(t_0)}:\mathcal{N}(\mu, \sigma) \)

- Manufacturing deficiencies, swelling and shrinkage of the profile, dimension and position of the locking excenters influence the distance between sash and frame: 
  \( y_{\text{gap}0\text{Pa}, z}:\mathcal{N}(\mu, \sigma) \)

- Rigidity of the frame and wearing of the hinges varies in function of wind pressure: 
  \( y_{\text{gap}600\text{Pa}, z(t)}:\mathcal{N}(\mu, \sigma) \)

- Parameters of the Burger’s relaxation model: \( E_1, E_2, \eta_1, \eta_2 \)
The airtightness estimation model

Modeling the stochastic parameters using the Monte Carlo simulation

The simulation model:

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

Input parameters:
- \( y_{\text{gap}0\text{Pa},z} \sim N(\mu, \sigma) \)
- \( y_{\text{gap}600\text{Pa},z} \sim N(\mu, \sigma) \)
- \( y_{\text{seal}(t0)} \sim N(\mu, \sigma) \)
- \( E_1 \sim N(\mu, \sigma) \)
- \( E_2 \sim N(\mu, \sigma) \)
- \( \mu_1 \sim N(\mu, \sigma) \)
- \( \mu_2 \sim N(\mu, \sigma) \)
Reliability test on a window specimen

Properties of the window:
• Made by a hungarian producer, Holz team Ltd., type ClimaTrend 68
• Dimensions: 1480x1240 mm
• Profile was 68 mm thick, with double glazings
• ROTO NT type hinges with 6 locking points

Testing procedure:
• Model’s input parameters determined by laboratory tests
• Running the Monte-Carlo simulation model
• Fitting distribution functions on results
• Representing the values belonging to the 95% percentile
Results of the reliability model:

Air tightness distributions simulated with the model:
Estimating the air tightness performance

The estimated distribution functions of the air tightness at 95% in function of opening cycles:
Conclusion

- The initial air tightness of a window changes over time, the first type prototype testing prescribed by regulations does not take into account this change.
- The introduced Gap Closure Index handles the gap variations over time.
- The developed model is able to estimate the air tightness of a window during its life cycle.
- With the help of the model we can determine the adjusting time of a window.
- More model validation tests must be run.
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Thank you for your attention