TOPIC:

Mechanical, Durability, Acoustic tests and Thermal simulations of Indresmat window frame.

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CONCTRACT: **The tests have been performed within H2020 MEZeroE open innovation test bed (OITB) project framework.**
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1 BASICS OF THE STUDY

- GRANT AGREEMENT NUMBER 953157 - MEZeroE: H2020-NMBP-TO-IND-2018-2020 / H2020-NMBP-TO-IND-2020-twostage.
- EN 12697-46:2020 Bituminous mixtures – Test methods – Part 46: Low temperature cracking and properties by uniaxial tension tests
- EN 514:2018 Plastics - Poly(vinyl chloride) (PVC) based profiles - Determination of the strength of welded corners and T- joints
- EN 14351-1+A2:2016-10 Windows and doors -- Product standard, performance characteristics -- Part 1: Windows and external pedestrian doorsets.
- EN 13165:2012+A2:2016 Thermal insulation products for buildings -- Factory made rigid polyurethane foam (PU) products – Specification.
- EN 12091:2013 Thermal insulating products for building applications. Determination of freeze-thaw resistance.
- EN ISO 12354-1:2017 Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms.
- EN ISO 12354-2:2017 Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 2: Impact sound insulation between rooms.
- EN ISO 13788:2012 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods.
- EN ISO 10211:2017 Thermal bridges in building construction — Heat flows and surface temperatures — Detailed calculations.
- EN ISO 10077-2:2017 Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 2: Numerical method for frames.
- EN ISO 10456: 2007 Building materials and products — Hygrothermal properties — Tabulated design values and procedures for determining declared and design thermal values.
- Results of technical tests carried out by:
  - the accredited Building Materials and Structures Research Laboratory of the Cracow University of Technology AB 1251 outside the scope of accreditation,

- the accredited Deformations and Vibrations of Structures Laboratory of the Cracow University of Technology AB 846 outside the scope of accreditation,
- the Road Materials and Pavements Research Laboratory of Cracow University of Technology,
- the Building Design and Building Physics Research Laboratory of Cracow University of Technology.

2 PURPOSE AND SCOPE OF TESTS

The purpose of the study was to determine the following Indresmat KLIMA-PUR window frame properties:

I. Low temperature cracking.

II. Durability

a. Resistance to artificial ageing by exposure to freeze-thaw. Diagnostics of durability due to ageing included features not defined in the standard. The tests included:

- Mechanical test before artificial ageing - Strength of corners according to EN 514,
- Freeze-thaw according to EN 13165 with modification,
- Mechanical test after artificial ageing - Strength of corners according to EN 514.

b. Resistance to accelerated ageing by exposure to temperature in accordance with the requirements of EN 13165. Diagnostics of durability due to accelerated ageing included features not defined in the standard. The tests included:

- Mechanical test before artificial ageing - Strength of corners according to EN 514,
- Accelerated ageing according to EN 13165,
- Mechanical test after artificial ageing - Strength of corners according to EN 514.

III. Direction-averaged junction velocity level difference for connector or for connection model.

IV. Internal surface temperature.

In accordance with the arrangements with the Industrial Partner, the scope of the tests included two type of window frames. The frames samples for the tests were delivered by Indresmat, and according to Figure 2 ÷ Figure 5 were marked in the CUT laboratory according to Table 1.

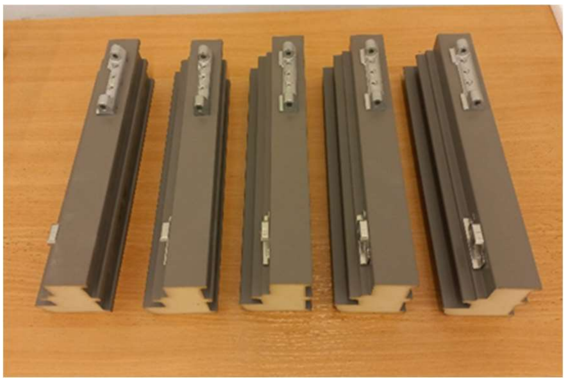


Figure 1 IWF-16: samples of window frame for the tests

Figure 2 IWF-10: samples of window frame for the tests

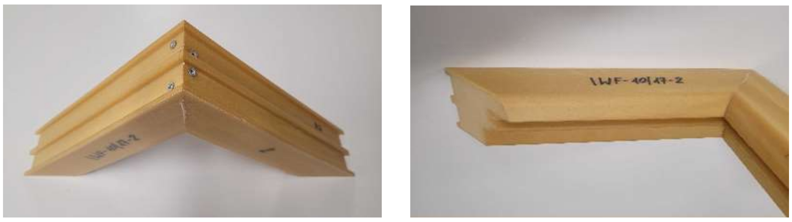


Figure 3 IWF-10/17: samples of window frame for the tests

Figure 4 IWF-10/20: samples of window frame for the tests

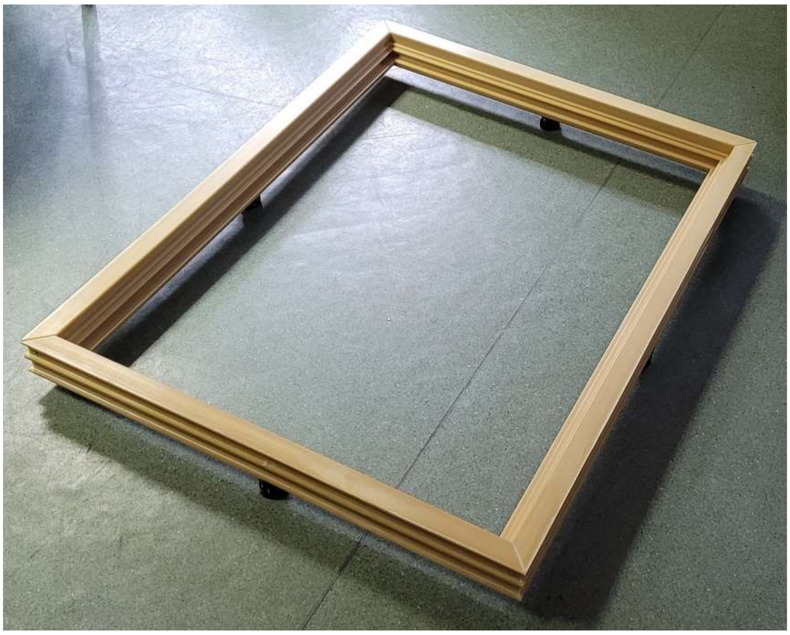


Figure 5 IWF-27: sample of window frame for the tests

Table 1 Marking of samples for testing

Symbol	Test
IWF-16	Low temperature cracking
IWF-10	Strength of corners /reference mechanical test before artificial ageing/
IWF-10/17	Strength of corners /after freeze -thaw artificial ageing/
IWF-10/20	Strength of corners /after accelerated ageing/
IWF-27	Direction-averaged junction velocity level difference for connector or for connection model

3 TESTS METHODS

3.1 Low temperature cracking

The goal of the low temperature cracking measurement is to determine the resistance of tested element against low temperature cracking performed by measuring temperature and force. The measurements were carried out in the Road Materials and Pavements Research Laboratory (L-5) of CUT according to EN 12697-46, with modifications.

The tests were carried out on a MTS Landmark servohydraulic testing system of 100 kN equipped with special grips for fixing the sample and Mytron temperature chamber to perform cooling tests to the temperature of –40 °C (Figure 6).

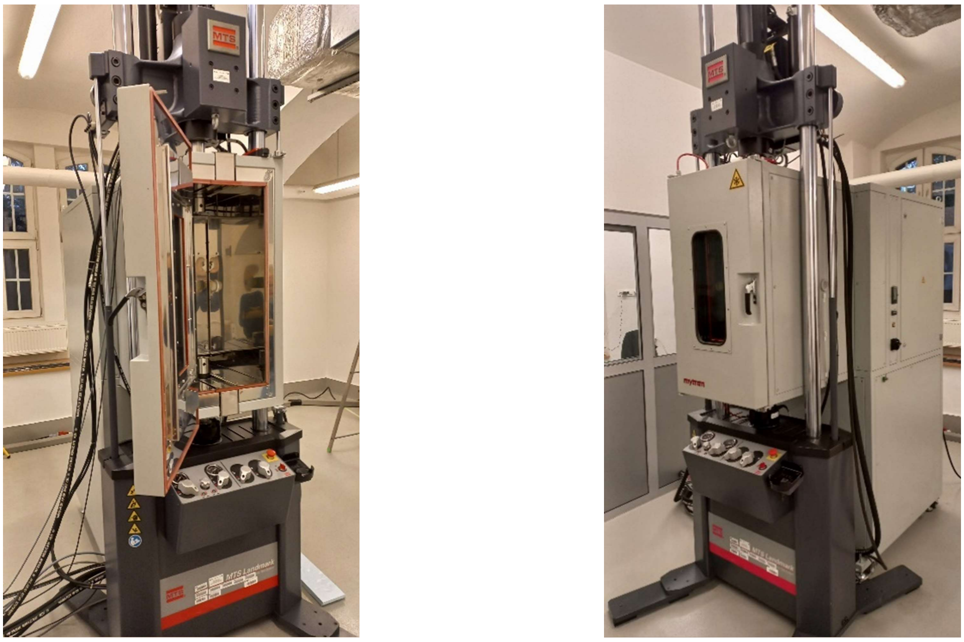


Figure 6 Testing stand used in the low temperature cracking test (existing facilities)

The tests were carried out on five samples cut from the window frame (Figure 1). The dimensions of the samples in the cross-section result from the dimensions of the cross-section of the tested window frame. The length of the samples is 300 ± 1 mm. The cross-sectional area of the sample was 3134 mm^2. The scheme of window frame cross-section with lines indicating the centroid of the cross-sectional area are shown in Figure 7.

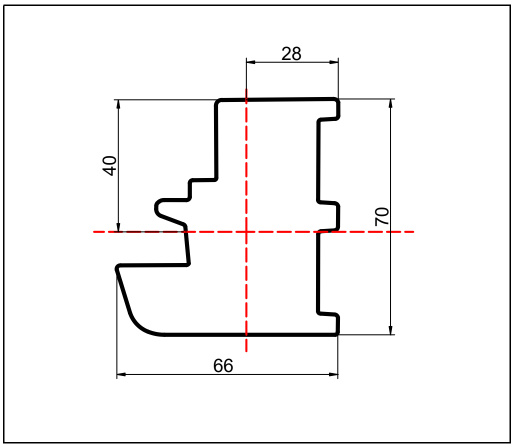
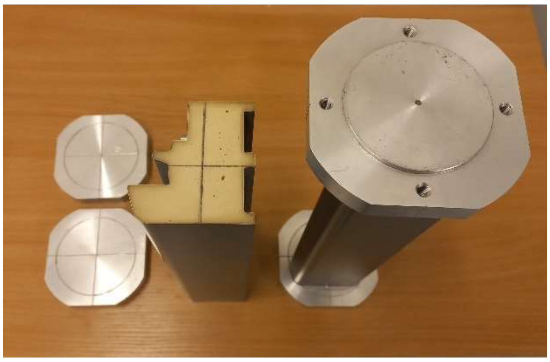


Figure 7 Scheme of the window frame cross-section [mm]

All specimens provided for testing by a producer must be in good technical condition and without visible damages (caused e.g. by transportation). Damaged specimens are disqualified from testing.

The sample was fixed to a stiff steel plates using an appropriate adhesive. The steel plates are then mounted to the spherical joints, swivel jig and clamps. The sample was conditioned before the test for a minimum of 4 hours at the test start temperature. The sample during preparation for testing is shown in Figure 8. The set of samples and the sample prepared for assembly in the machine are shown in Figure 9.



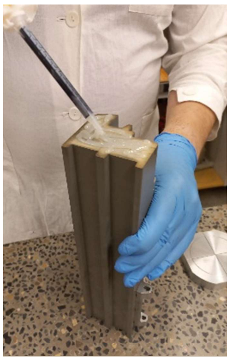


Figure 8 Sample during preparation for testing

Figure 9 Set of samples and the sample prepared for assembly in the MTS machine

The prepared sample is mounted vertically in the MTS machine under hydraulic piston. The sample mounted in the machine is shown in Figure 10.

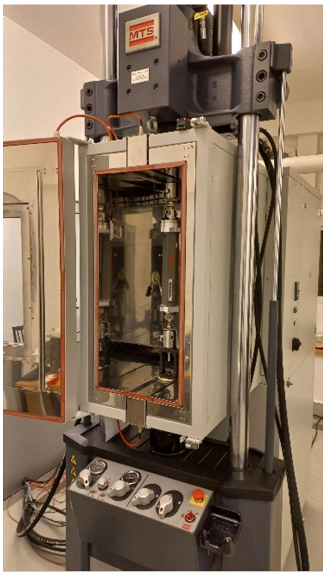


Figure 10 Sample mounted in the MTS machine

3.1.1 Testing procedure

The testing stand is equipped with sensors, controlling force, displacement and the temperature of the sample. Signals are acquired by the calibrated, multichannel acquisition system.

In the first step, the initial temperature is stabilized. Then the test control program is launched. The preload is applied to eliminate slack in the system. The vertical displacement of the sample is blocked.

In the second step, the sample is held at a constant length while its temperature is decreased with time, at a rate of 10 ± 1 °C per hour. Because of the prohibited thermal shrinkage (thermal strain), the sample is subjected to cryogenic tensile stress. Testing protocol is stopped when the failure of the specimen will occur or the final temperature will be reached. The final cryogenic temperature of the test is equal to -25 ± 1 °C.

The cryogenic stress is calculated as the ratio of the thermally induced force resulting from blocked thermal deformations to the cross-section area of the tested sample.

3.1.2 Observations and measurements

Force and temperature are measured during the test. The accuracy class of force transducers of the testing machine equals 0.5 in a range of the force value from 1% to 100%. The climatic chamber allows testing at temperatures from +60 °C to –40 °C. The temperature is measured with an accuracy of ±1°C.

3.1.3 Evaluation criteria

The evaluation criterion includes the test final temperature. The final, required cryogenic temperature of the test was set at -25 ± 1 °C.

There are two possible modes of ending the test:

- failure of the tested specimen before the test final temperature is reached. Cryogenic failure temperature is reported, failure cryogenic stress is calculated. The specimen did not meet the required temperature evaluation criterion.

- no failure of the tested specimen before the test final temperature is reached. The final cryogenic temperature of the test is reported (–25 ± 1 °C), maximal cryogenic stress is calculated. The specimen met the required temperature evaluation criterion.

The test specimens were tested at starting temperature: 22 ± 1 °C, humidity: 30–70%. The test duration resulted from the assumed test final temperature.

3.2 Strength of corners

The strength of corners of window/casement frame was determined in the accredited Building Materials and Structures Research Laboratory of the Cracow University of Technology AB 1251 outside the scope of accreditation according to EN 514. The purposes of the tests were to determine strength of corner of window (casement) frame. The testing procedure is dedicated for polyurethane window (casement) frames.

The tests were carried out on a universal testing machine Z100 Zwick/Roell – **LB 039** equipped with set of rollers. Dimensions of the tested window/casement corner are given in Figure 11.

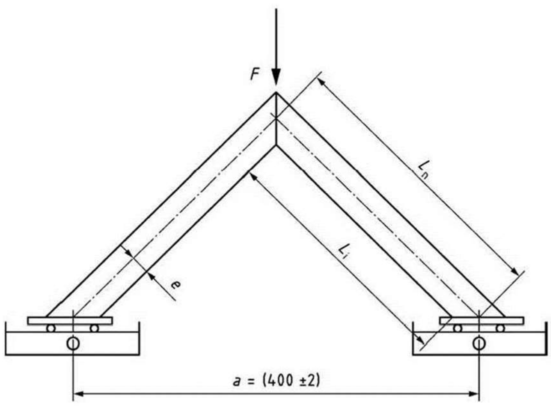


Figure 11 Dimensions of the tested window/casement corner

Three samples of corners were tested in each test (Figure 2 ÷ Figure 4). The test specimens were conditioned and tested at the temperature of (23 ± 5) °C.

3.3 Durability

The durability tests were determined in the accredited Building Materials and Structures Research Laboratory of the Cracow University of Technology AB 1251 outside the scope of accreditation. According to point 4.15 EN 14351-1:2006+A2:2016 durability of windows depends, among other things, on the durability of the characteristics of individual components and materials. KLIMA-PUR window frames are made of polyurethane foam, therefore the requirements of EN 13165:2012+A2:2016 with modification agreed with Indresmat were used to assess durability.

3.3.1 Freeze-thaw resistance

The freeze-thaw resistance of three window frame corners - samples **IWF-10_17** was determined according to a modified method included in Annex E.6 EN 13165. The samples were not submitted to water absorption by diffusion or total immersion before freeze-thaw test. The test method according to Annex E.6 EN 13165 consists of exposing test specimens to 300 freeze-thaw cycling test. The modification of the EN 12091 recommendations consisted in extending the temperatures to the range of -40°C to +80°C and extending the freezing-thawing cycle to 8 hours in accordance with Figure 12.

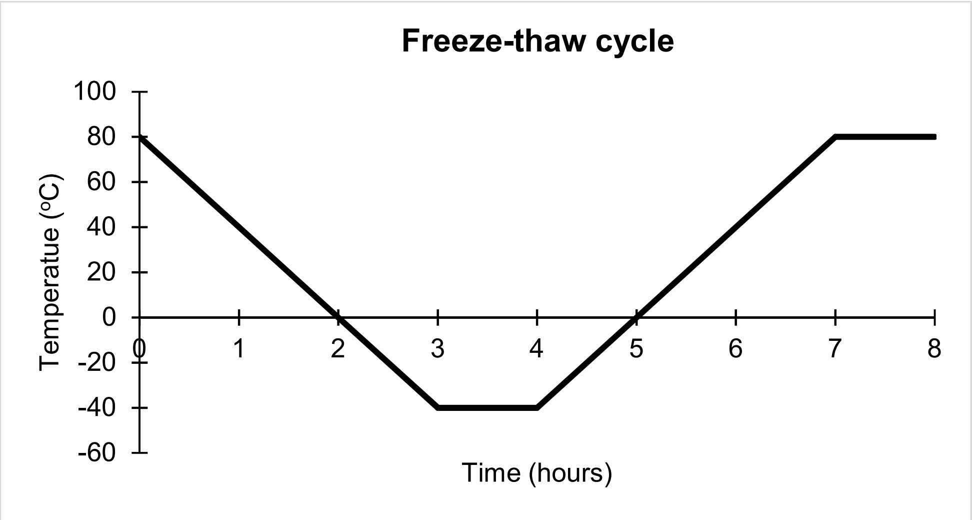


Figure 12 Freeze-thaw cycle

The freeze-thaw tests were performed in Climatic chamber **LB 222** (Figure 13). The test samples were conditioned for 6 h at (23 ± 5) °C. The exposure to 300 freeze-thaw cycles was carried out from February to May 2023 and lasted 100 days.

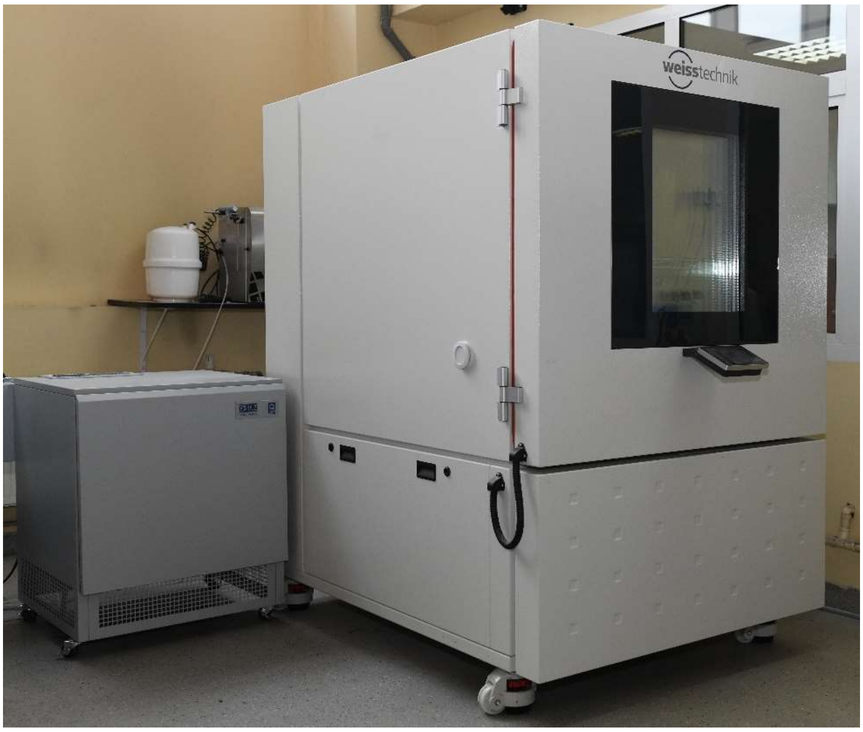


*Figure 13 Climatic chamber **LB 222** (purchased with MEZeroE funds)*

3.4 Accelerated ageing procedure

The accelerated ageing resistance of three window frame corners - samples **IWF-10_20** was determined according to Annex C EN 13165. The test method consists of storing test specimens at (70 ± 2) ºC for (175 ± 5) days. The test was conducted by ventilated oven with temperature control **LB 114** (Figure 14). Test samples were conditioned at (23 ± 3) ºC and (50 ± 10)% relative humidity for 16 h. The accelerated ageing was carried out from September 2022 to March 2023.

*Figure 14 Ventilated oven with temperature control **LB 114** (existing facilities)*

3.5 Direction-averaged junction velocity level difference for connector or for connection model

The goal of direction-averaged junction velocity level difference for connector or for connection model is to determine of ability to transfer vibrations through node with tested connector applied performed by measuring vibration velocity difference between node ends. Tested parameters: provides impulse force and measures acceleration of system response were determined according to our own procedure based on EN ISO 12354-1 and EN ISO 12354-2.

The direction-averaged junction velocity level difference tests of window frame were carried out in the Laboratory of Deformation and Vibration Testing of Buildings of Cracow University of Technology. The test called VAVLD was performed 6 times on window frame Indresmat.

The tests were carried out by Dynamic exciter – tapping machine or modal hammer and IEPE accelerometers (designation of the device subject to supervision in the Laboratory accredited by PCA AB 0846).

Testing procedure:

1) Design test stand with consideration of testes connector and with regard to vibroacoustic coupling
    a. Ambient conditions must meet operating conditions of used equipment
2) Provide vibroisolation in tested specimen and impact source

3) Apply impact source to sample
    a. Both modal hammer and tapping machine is used. Results from tapping machine are preferable as long as no significant distortion is registered on accelerometers
4) Measure accelerations using IEPE accelerometers connected to specimen in front of and behind the connector
    a. Accelerometers should be detachable, installation of accelerometers should be done with resonant frequency higher than maximum measured frequency during test.

The tested window frame contains four nodes, therefore it was considered a connector.

The multiplication of measurement tests by the number of samples must be greater than or equal to 6. At least 3 test connectors must be used in the test procedure. The tested sample and the impact sources were vibroacoustic separated during the test. Vibration isolation of the threading machine and the tested sample was used.

A photograph of the test sample is shown in Figure 5, and the test stand is shown in Figure 15.

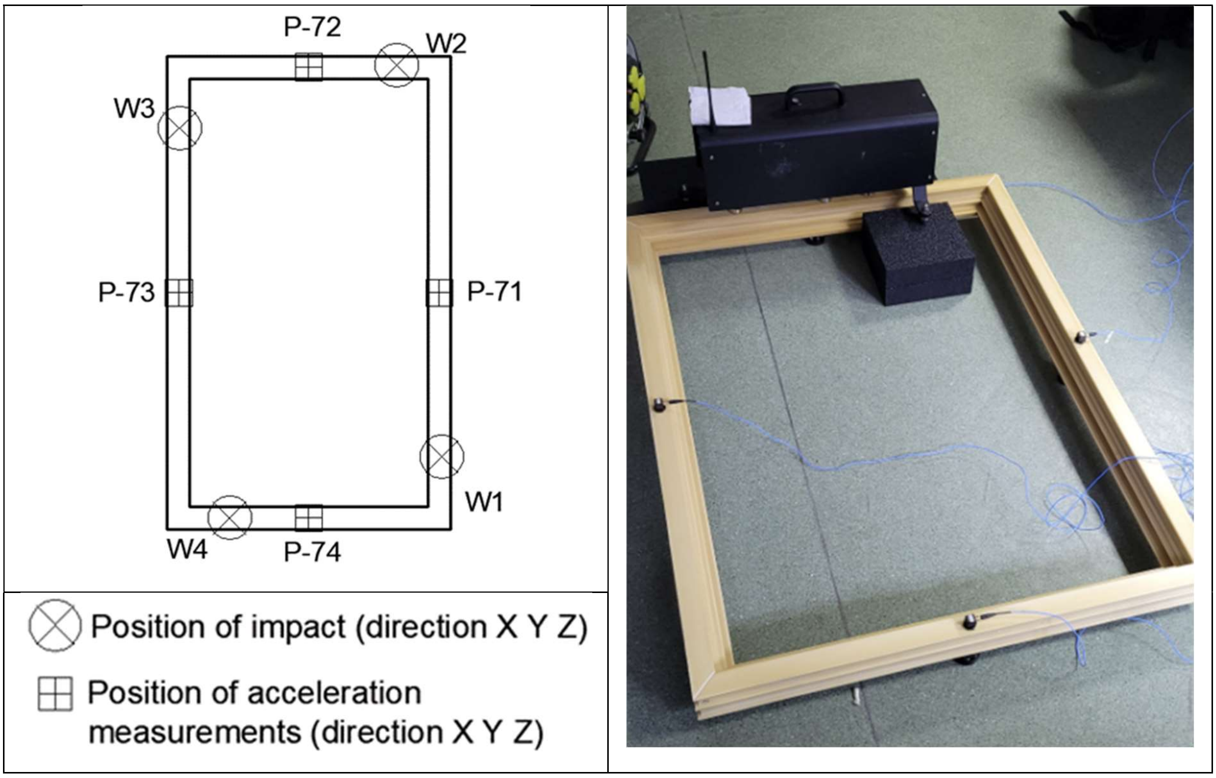


Figure 15 Test setup plan (left), in lab with tapping machine (purchased with MEZeroE funds) (right)

Vibration velocity level difference [dB] using mobility function (based on inertance function). Excitation with be done by modal hammer and tapping machine. Measured of specimen response is done by IEPE accelerometers. Test frequency will be limited to 5kHz if possible. Minimum frequency below 50Hz. Reproducibility of measurement is advised to be qual or below 3dB.

Following parameters will be evaluate: visible damages of the tested specimen, level difference changes in frequency domain. Evaluation criteria, threshold values and tolerances will be adjusted individually, due to innovative character of the testing procedure and novelty of tested specimens, not undergoing present standards or guidelines fitting exactly to this procedure.

Test 01: VAVLD window frame Indresmat

Window frame delivered by INDRESMAT partner. Test was aimed to check vibration velocity reduction in corners of window frame.

Vibroisolation of window frame (preventing coupling with different elements of lab room). Too soft vibroisolation provided nonlinear behaviour of window frame, too stiff created coupling with floor. Tapping machine had to be vibroisolated using rubber granulate to prevent coupling with other lab equipment. Test setup presented in Figure 15.

Testing conditions:

- T = 21 °C (CI95 %, 20.4;21.7) °C
- P_{atm} = 1001 hPa (CI95 %, 988;1020) hPa
- RH = 41 % (CI95%, 35;51)%

Single measurement cycle 8h, 6 cycles in total.

3.6 Internal surface temperature

The subject of the test are elements of the external shell of energy-efficient buildings and their interconnections with each other and their connections with the building structure. Procedure is aimed to issue an opinion on the compliance of the innovative design solution with the relevant standards. The purpose of the study is to check the critical surface humidity likely to lead to problems such as mould growth on the internal surfaces of buildings. The scope of application of the proposed procedure is dedicated to the components of external building shell, subjected to temperature difference, like opaque walls, windows etc.

The decrease of air temperature at the internal surface of building, especially of the thermal bridges, causes an increase in the relative air humidity, which may lead to the phenomenon of capillary condensation or saturation of the air with water vapour. Finally, an increase in the moisture content of the partition material may occur. Under such conditions, mould can grow intensively. In the procedure of checking the critical humidity it is important to indicate the lowest temperature on the inner (warm) surface of the tested joint. The identification of the lowest temperature can be carried out in two ways: computationally in a simulation software or by measurement in a laboratory or in existing buildings.

4 TESTS RESULTS

4.1 Low temperature cracking

The results of the tests carried out under normal operative conditions between August and October 2023 using the recommended method are given in Table 2. The relationship between cryogenic stress and the temperature are shown in Figure 16.

Table 2 Results of the tests

Specimen number	**Starting temperature**	**Maximum cryogenic stress**	**Final temperature**	**Failure mode**	**Evaluation of result**
1	22 ± 1 °C	1.19 MPa	-25 ± 1 °C	No failure of the specimen	The specimen met the evaluation criterion
2	22 ± 1 °C	1.47 MPa	-25 ± 1 °C	No failure of the specimen	The specimen met the evaluation criterion
3	22 ± 1 °C	1.34 MPa	-25 ± 1 °C	No failure of the specimen	The specimen met the evaluation criterion
4	22 ± 1 °C	1.27 MPa	-25 ± 1 °C	No failure of the specimen	The specimen met the evaluation criterion
5	22 ± 1 °C	1.53 MPa	-25 ± 1 °C	No failure of the specimen	The specimen met the evaluation criterion
Men value:		**1.36 MPa**			
Standard deviation:		0.14 MPa			
Coefficient of variation:		10.4%			

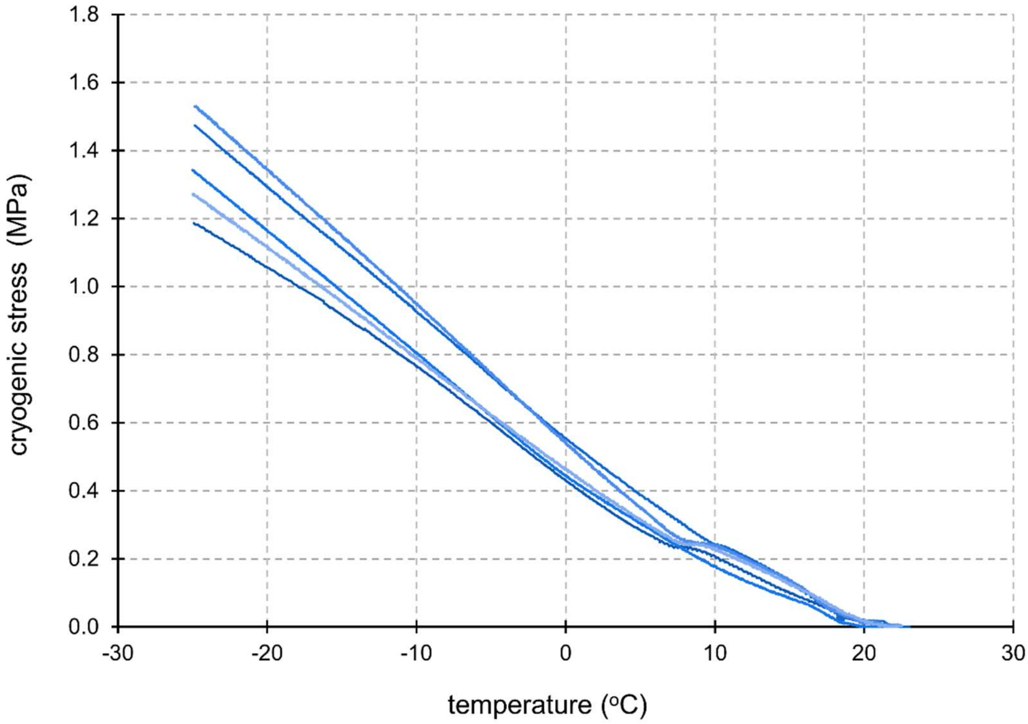


Figure 16 The relationship between cryogenic stress and the temperature

The condition of the sample is observed during the test. In the final phase of the test, freezing of the sample can be observed. A view of the sample in several stages of test is shown in Figure 17.

Figure 17 View of the sample at the beginning of the test (on the left), during the test and at the end of the test (on the right)

4.2 Durability

4.2.1 Strength of corners before ageing

The results of the tests on strength of corners before ageing, which tests were carried out on September 21, 2023 using the recommended method of EN 514 are given in Table 3. The plot of load and vertical displacement is shown in Figure 18.

Table 3 Strength of corners

Specimen ID	Failure load (N)	Inside length of the legs (mm)	Distance between the axes of rotation of the carriages (mm)	Failure stress (N/mm²)
IWF-10-1	687	199	392	3.2
IWF-10-2	735	198	391	3.4
IWF-10-3	720	198	391	3.3
			Average failure stress:	**3.3 N/mm²**
			Standard Deviation:	**0.1 N/mm²**
			Coefficient of Variation	**3.2%**

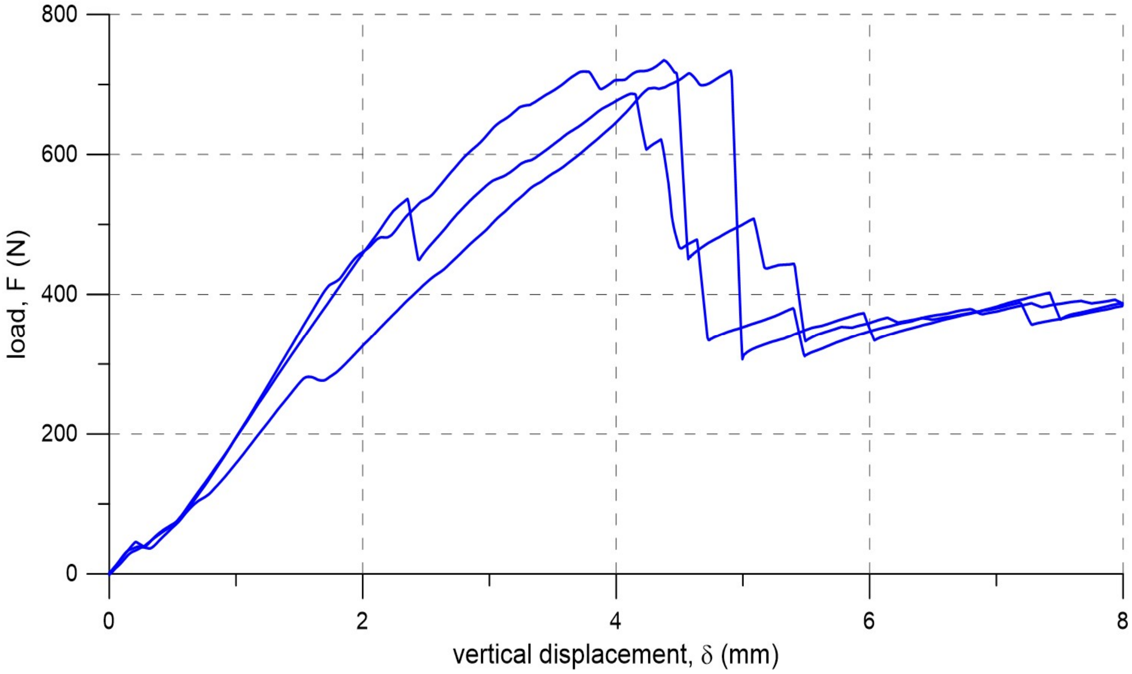


Figure 18 The relationship between load and vertical displacement of corners before ageing

The specimens IWF-10 during the test (strength of corners before ageing) are presented in Figure 19.

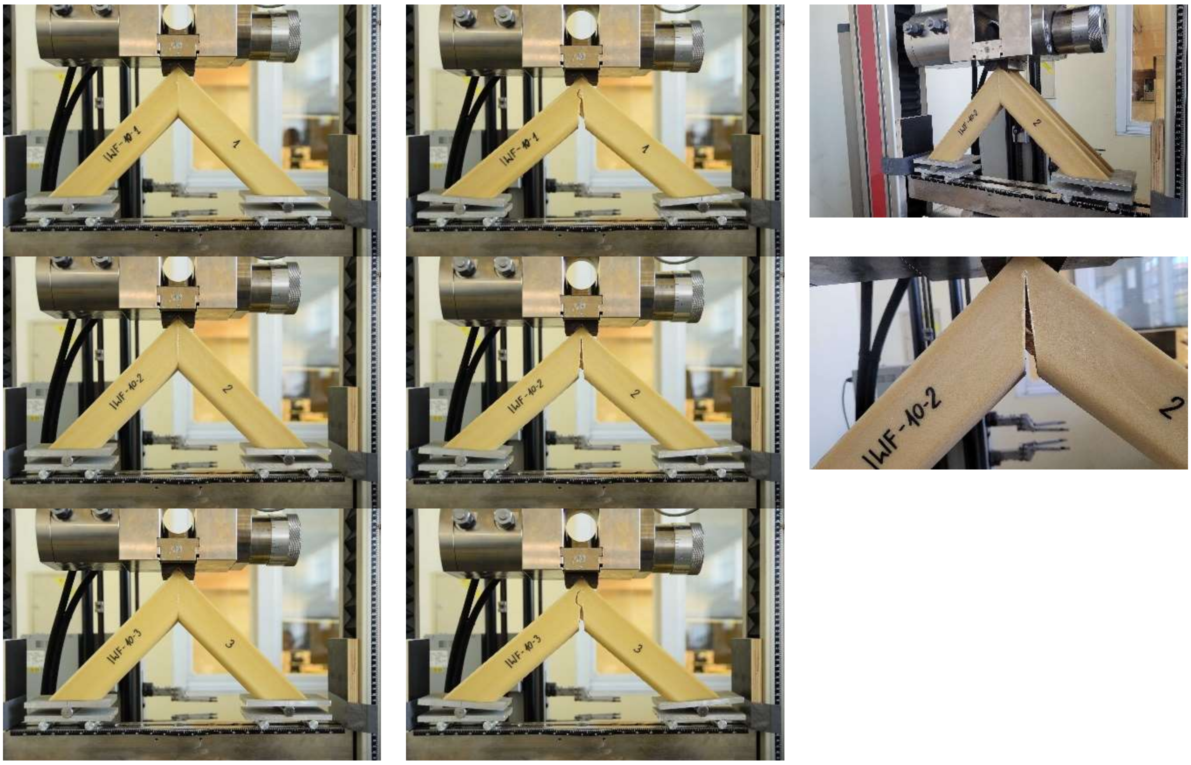


Figure 19 Specimens IWF-10 during the test of strength of corners before ageing (Jaws and handles for testing machines and Kit for testing materials and testing machine - Zwick Roell purchased with MEZeroE funds)

4.2.2 Strength of corners after freeze-thaw ageing

The results of the tests on strength of corners after freeze-thaw ageing which were carried out on September 21, 2023 using the recommended method of EN 514 are given in Table 4. The plot of load and vertical displacement is shown in Figure 20.

Table 4 Strength of corners after freeze-thaw ageing

Specimen ID	**Failure load (N)**	**Inside length of the legs (mm)**	**Distance between the axes of rotation of the carriages (mm)**	**Failure stress (N/mm²)**
IWF-10/17-1	609	199	392	2.8
IWF-10/17-2	550	199	392	2.6
IWF-10/17-3	424	199	392	2.0
			Average failure stress:	**2.5 N/mm²**
			Standard Deviation:	0.4 N/mm²
			Coefficient of Variation	17.9%

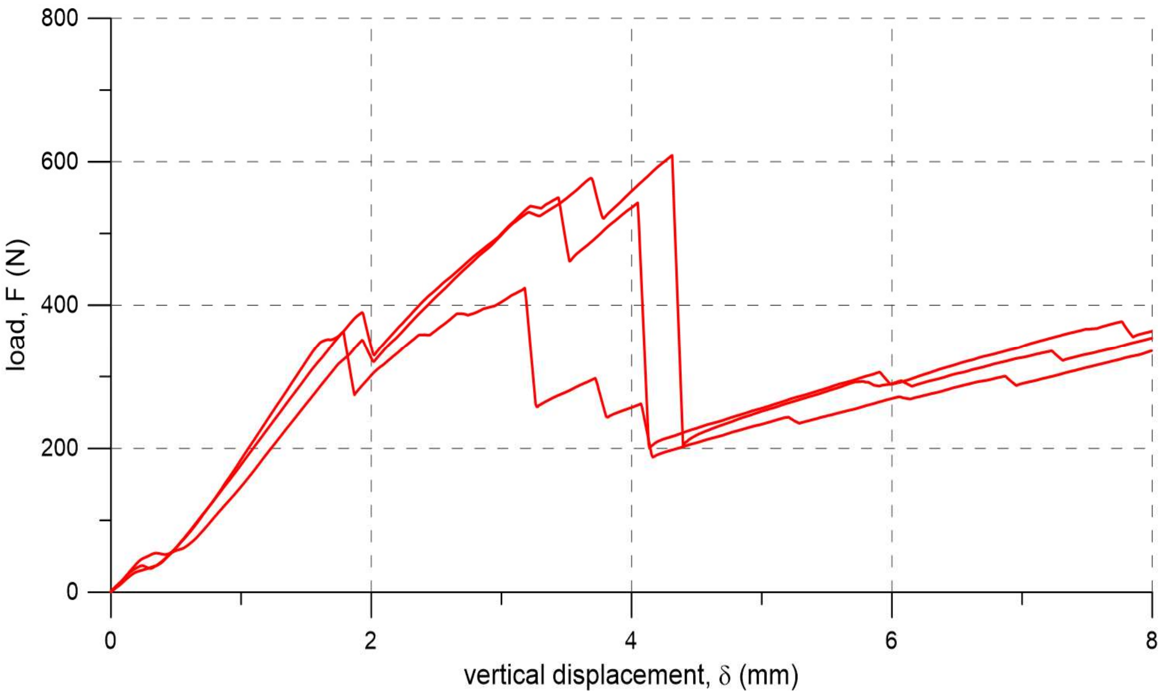


Figure 20 The relationship between load and vertical displacement of corners after freeze-thaw ageing

The specimens IWF-10/17 during the test (strength of corners after freeze-thaw ageing) are presented in Figure 21.

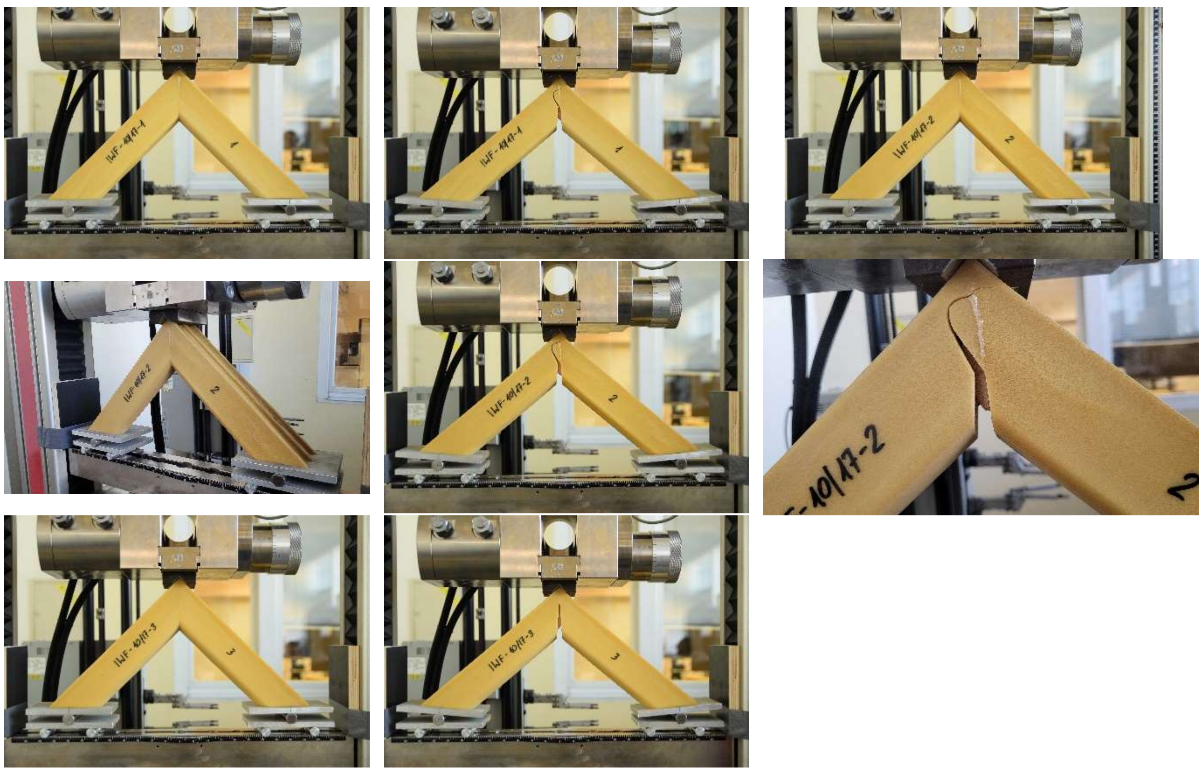


Figure 21 Specimens IWF-10/17 during the test of strength of corners after freeze-thaw ageing (Jaws and handles for testing machines and Kit for testing materials and testing machine - Zwick Roell purchased with MEZeroE funds)

4.2.3 Strength of corners after accelerated ageing

The results of the tests on strength of corners after accelerated ageing, which were carried out on September 21, 2023 using the recommended method of EN 514 are given in Table 5. The plot of load and vertical displacement is shown in Figure 22.

Table 5 Strength of corners after accelerated ageing

Specimen ID	**Failure load (N)**	**Inside length of the legs (mm)**	**Distance between the axes of rotation of the carriages (mm)**	**Failure stress (N/mm^2)**
IWF-10/20-1	654	199	392	3.0
IWF-10/20-2	632	199	392	2.9
IWF-10/20-3	600	199	392	2.8
			Average failure stress:	**2.9 N/mm^2**
			Standard Deviation:	0.1 N/mm^2
			Coefficient of Variation	4.3%

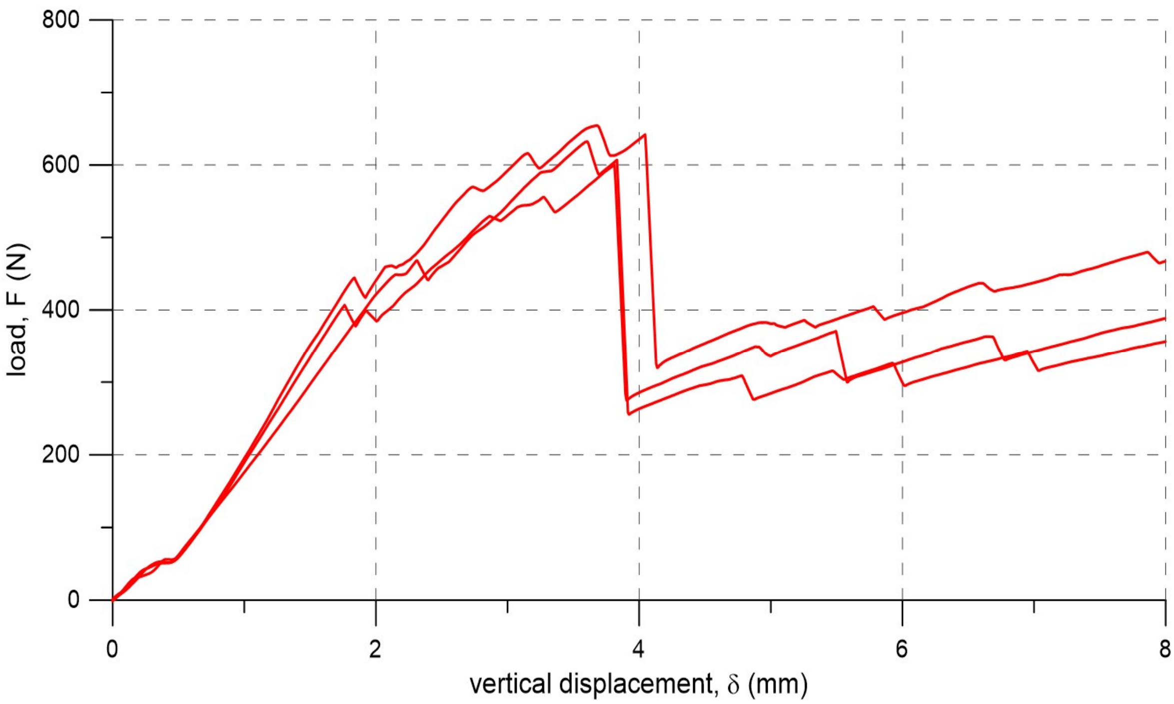


Figure 22 The relationship between load and vertical displacement of corners after accelerated ageing

The specimens IWF-10/20 during the test (strength of corners after accelerated ageing) are presented in Figure 23.

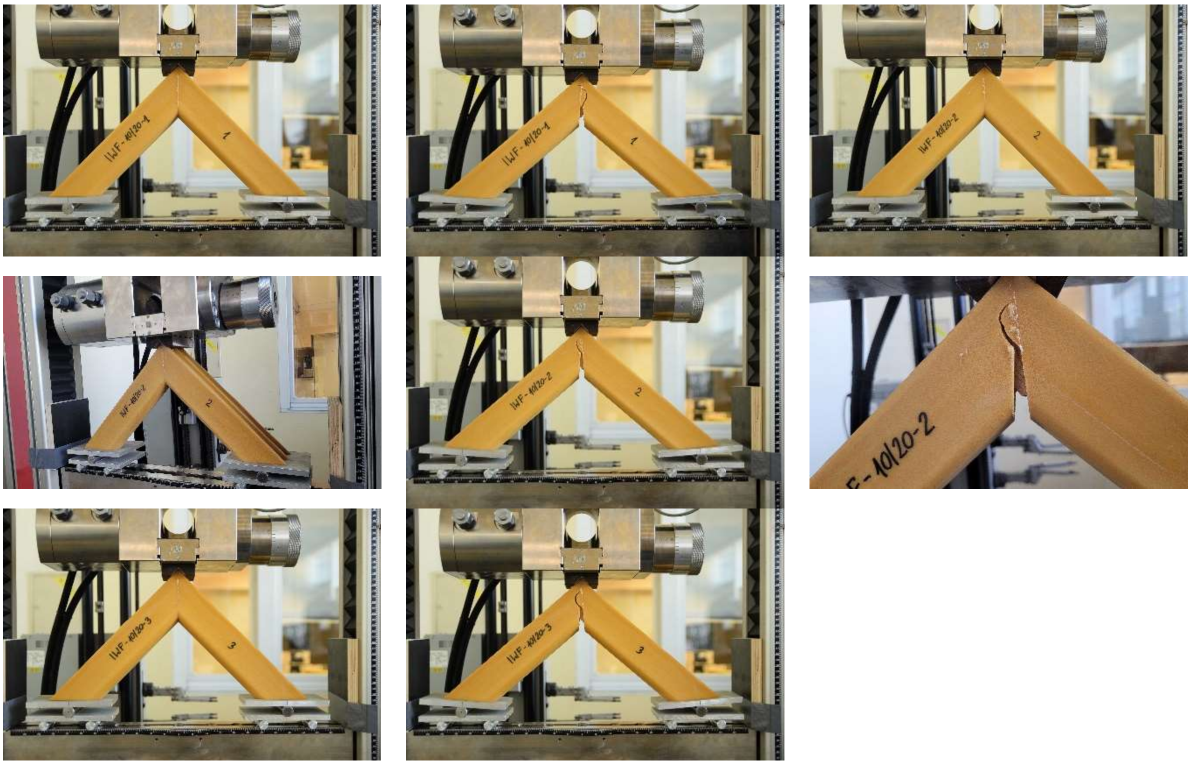


Figure 23 Specimens IWF-10/20 during the test of strength of corners after accelerated ageing (Jaws and handles for testing machines and Kit for testing materials and testing machine - Zwick Roell purchased with MEZeroE funds)

4.2.4 Resistance to artificial ageing by exposure to freeze-thaw

The average test results of strength of corners before and after ageing by freeze-thaw are presented in Table 6.

Table 6 Resistance to artificial ageing by exposure to freeze-thaw

Specimen ID	**Average Failure stress (N/mm^2)**	**Standard Deviation (N/mm2)**	**Coefficient of Variation (%)**
before ageing	3.3	0.1	3.2
after freeze-thaw ageing	2.5	0.4	17.9

4.2.5 Resistance to accelerated ageing

The average test results of strength of corners before and after accelerated ageing are presented in Table 7.

Table 7 Resistance to accelerated ageing

Specimen ID	**Average Failure stress (N/mm^2)**	**Standard Deviation (N/mm2)**	**Coefficient of Variation (%)**
before ageing	3.3	0.1	3.2
after accelerated ageing	2.9	0.1	4.3

4.3 Direction-averaged junction velocity level difference for connector or for connection model

The results of the tests carried out on September 2, 2023 using the recommended method are given in Table 8. The velocity level difference from source points W1÷W4 are shown in Figure 24 ÷ Figure 28.

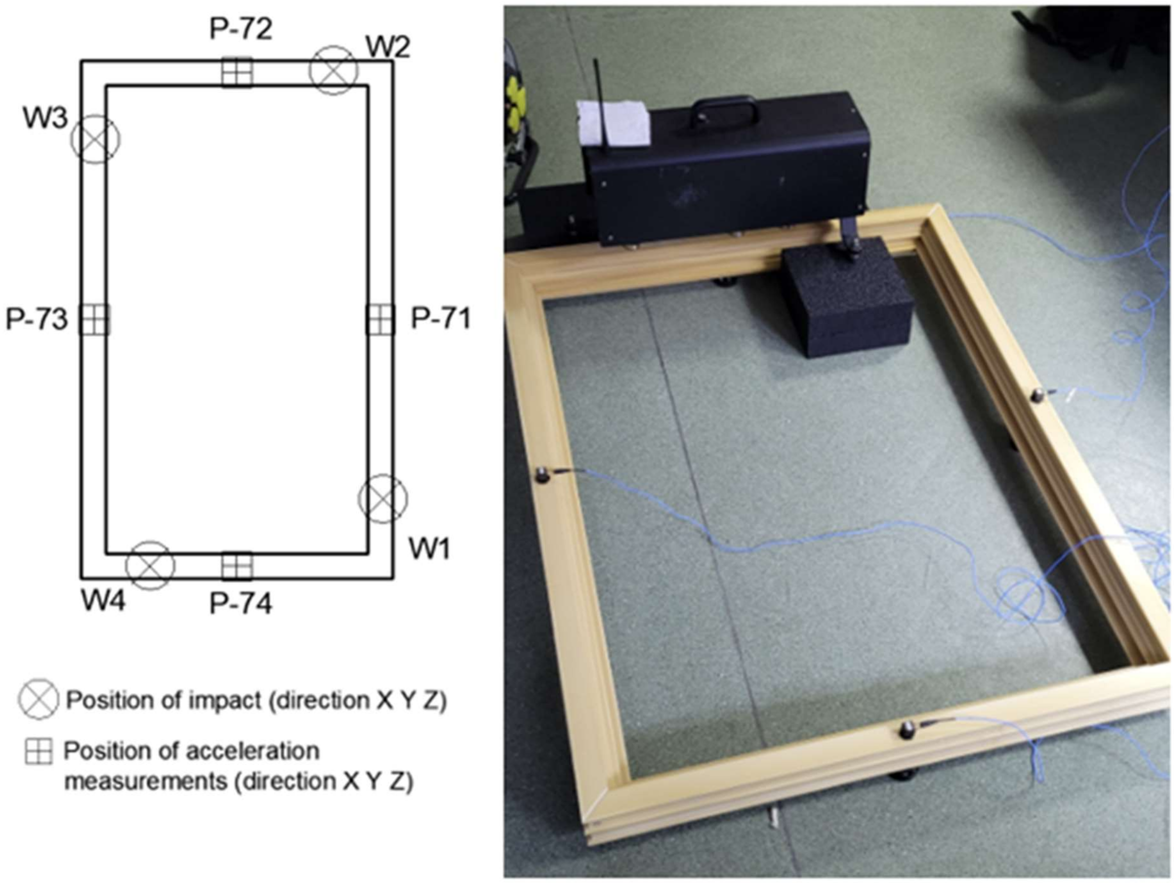


Figure 24 Test setup plan (left), in lab with tapping machine (right)

Table 8 Observations during the test

Device	Observations
Tapping machine	IEPE accelerometers tends to exhibits high distortions due to high impact force. Tapping machine may not be applicable as allrounder impact source for this test
IEPE accelerometers	Randomly, accelerometers adhesive lost its bearing capacity and disconnects from structure. As long as accelerometers must be removable from measured specimen, this problem can not be mitigated.
Modal hammer	No problems occurred

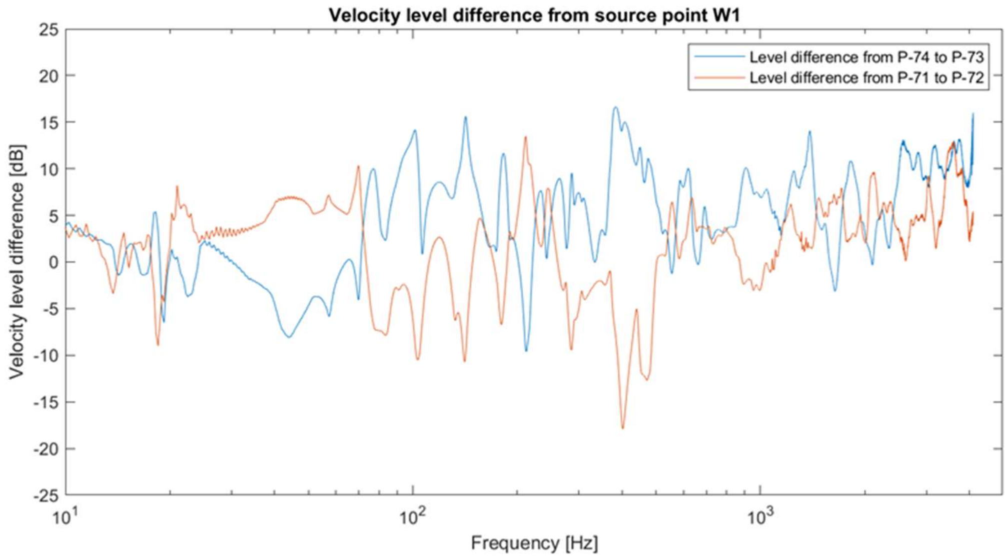


Figure 25 Velocity level difference from source point W1.

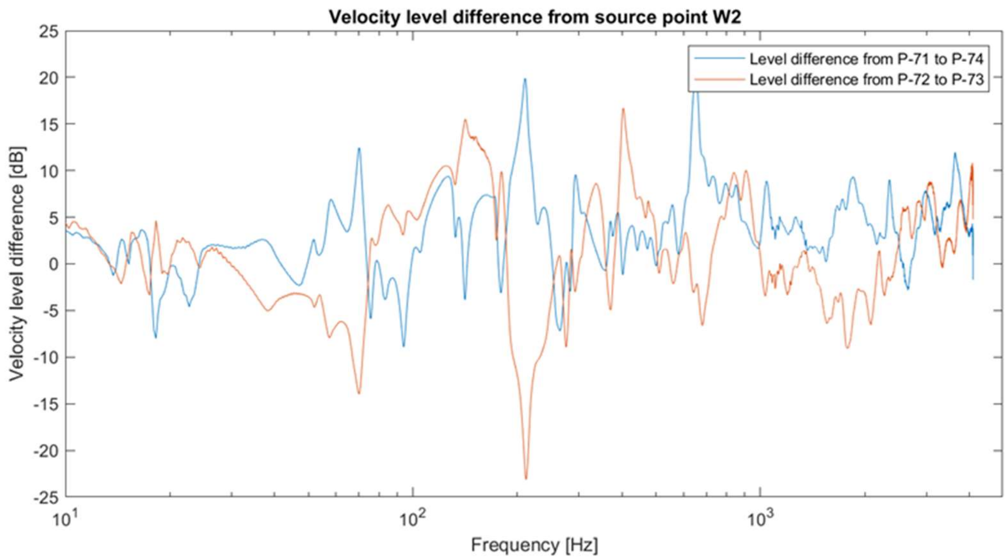


Figure 26 Velocity level difference from source point W2.

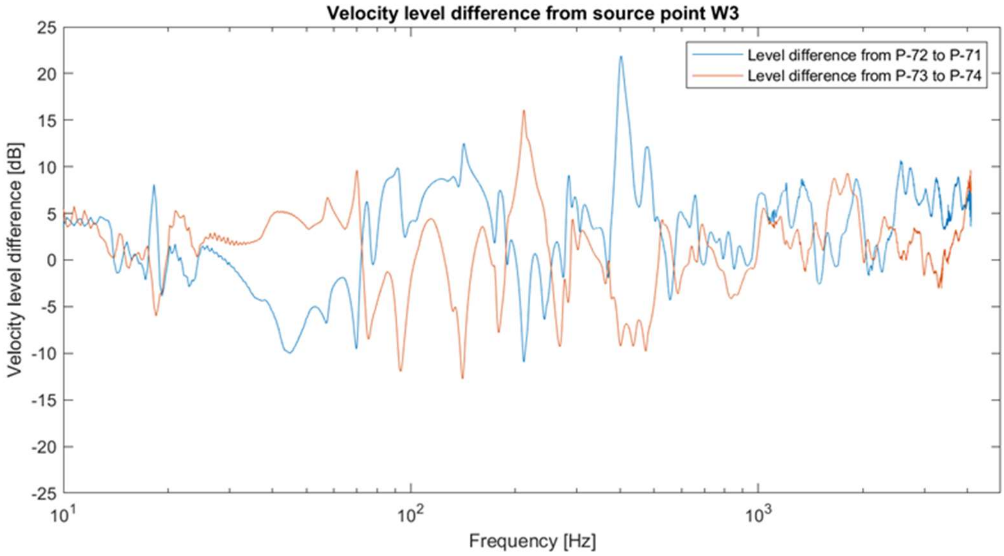


Figure 27 Velocity level difference from source point W3.

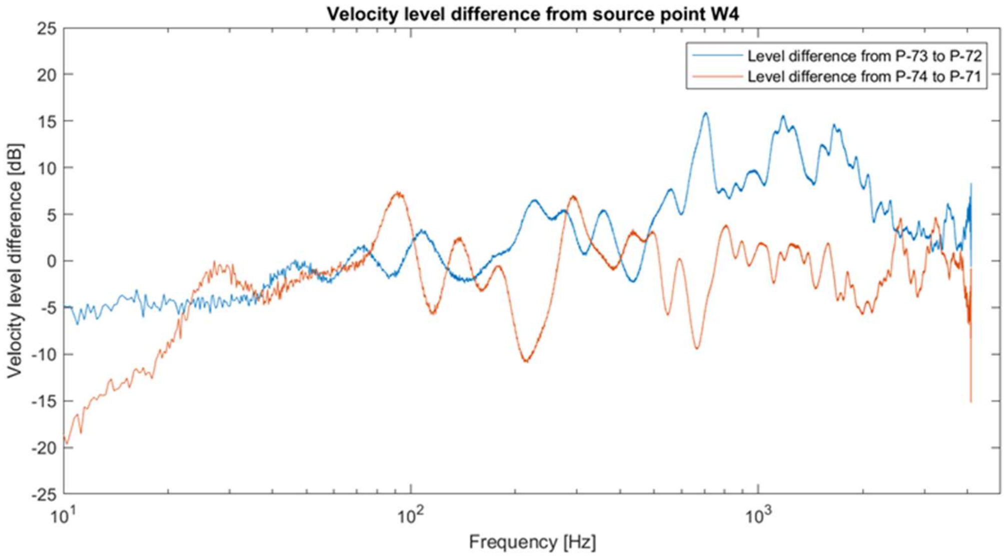


Figure 28 Velocity level difference from source point W4.

Photos of window frame during the test are presented in Figure 29.

Figure 29 Photos of window frame during the test

4.4 Internal surface temperature to avoid surface condensation.

1. Identification of the lowest internal surface temperature θ_{si} of the tested joint was conducted by means of the computer software Therm 7.6 (Figure 30 & Figure 31). Two assemblies have been simulated. Boundary conditions: internal air temperature +20°C, external air temperature -20°C. It must be emphasized that the calculated below values of the temperature factor f_{Rsi} are independent of the assumed boundary conditions.

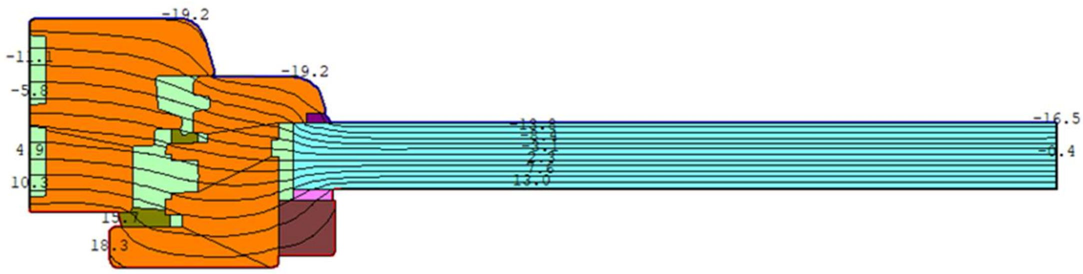


Figure 30 Frame edge

The lowest temperature of internal frame surface was equal to 14.1°C, at the point of contact between the main frame and the seal.

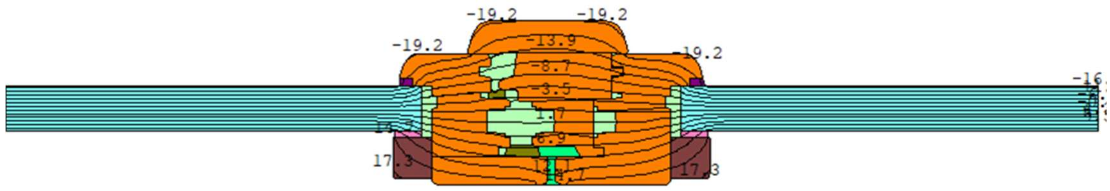


Figure 31 Frame central part

The lowest temperature of internal (visible) frame surface was equal to 13.6°C, the lowest temperature of the surface inside of the opened to internal environment central cavity was 6.6°C.

2. Calculation of temperature factor at the internal surface:

$$f_{R_{si}} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e}$$

- where: θ_{si} - internal surface temperature, θ_e – external air temperature, θ_i - internal air temperature. According to the standard EN 13788, for condensation or mould growth upon window surfaces, an internal surface thermal resistance of 0.13 m^2·K/W shall be taken if there are no other national standards.
- f_{Rsi} (14.1°C) = 0.86
- f_{Rsi} (13.6°C) = 0.84
- f_{Rsi} (6.6°C) = 0.67

3. Identification of the climate conditions and the intended building use.

It was assumed that the internal air temperature in winter is 20°C, internal humidity class 3 as for high occupancy, external temperature 0°C and the external air relative humidity equal to 85%.

4. With a maximum acceptable relative humidity of window frame at the surface φ_{sicr} equal to 100% acc. to the standard EN ISO 13788, the minimum acceptable surface temperature is for the given boundary conditions equal to 11.1 °C and the minimum temperature factor:

$$f_{Rsi,min} = 0.56$$

5. Criteria for accepting test results

   In order to avoid mould growth it is necessary to satisfy the following inequality:

$$f_{Rsi} > f_{Rsi,min}$$

   Test result in accordance with the standard EN 13788 is positive if the above inequality is satisfied.

6. Final conclusions

   Because all the above calculated three values of f_{Rsi} are bigger than the $f_{Rsi,min}$ value it must be concluded in the assumed internal conditions there is no risk of condensation on the internal surface of edge and central window frames, even within the open cavity of central frame.

   If a specified glazing package with a metal spacer is used, it is advised to check the temperature at the point of contact between the internal glass and the seal.

   The threshold value $f_{Rsi,min}$ is sensitive to the assumed local internal and external climate conditions.