Seminar on October 14, 2025
Wood Science & Engineering, College of Forestry, Oregon State University

Next generation of connectors for protection of timber structures against earthquakes and strong winds

Arkadiusz Kwiecień
(Poland)

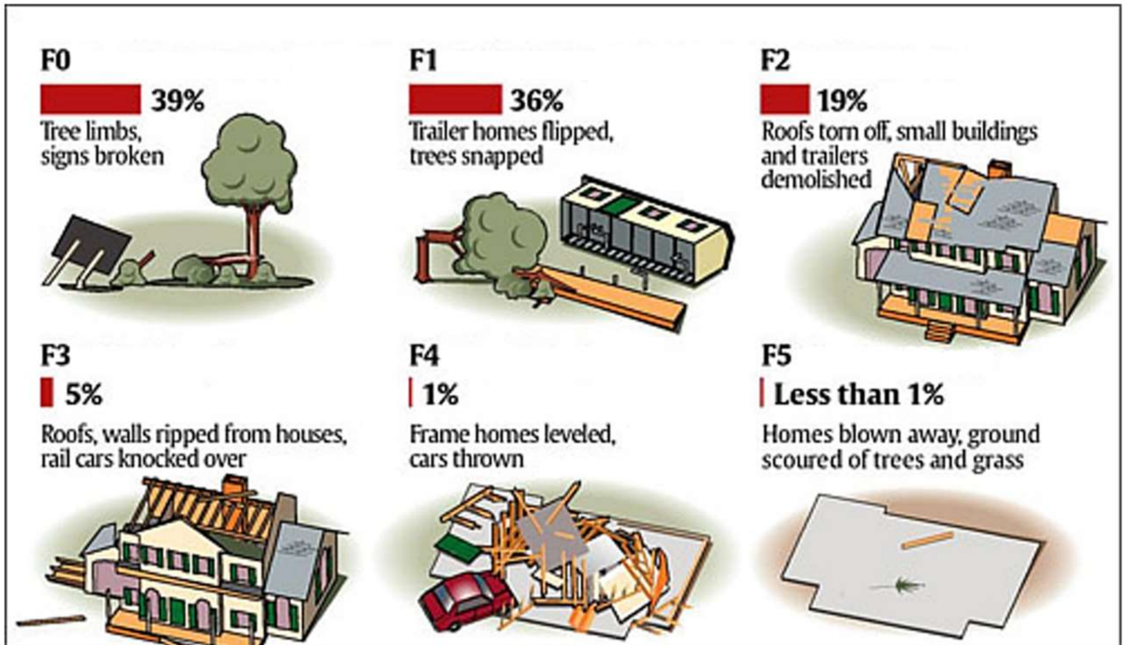
FLEX AND ROBUST SYSTEMS

Cracow University of Technology

MEZeroE project is a project receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 953157.

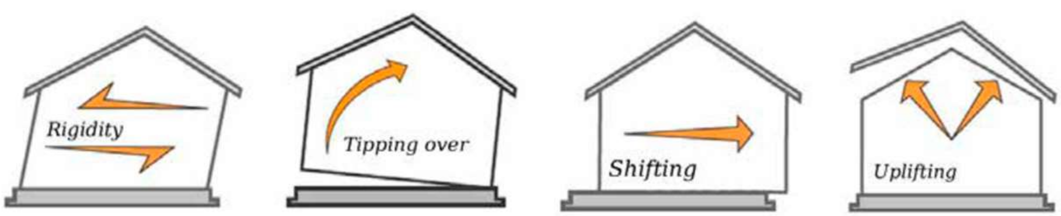
MEZEROE

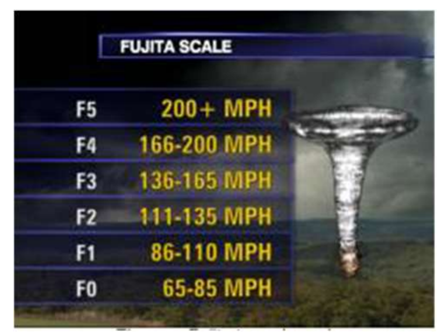
Catastrophic influences on buildings – tornados



Source: Storm Prediction Center, National Weather Service

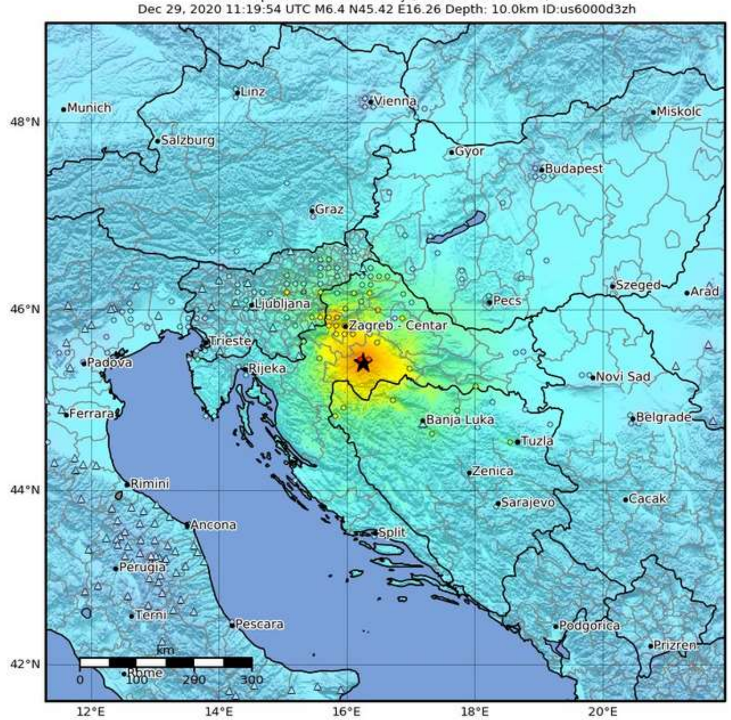
By Bob Swanson and Dave Merrill, USA TODAY





2020 Petrinja earthquake (29 December 2020)

Macroseismic Intensity Map USGS
ShakeMap: 3 km WSW of Petrinja, Sisačko-Moslavačka, HR
Dec 29, 2020 11:19:54 UTC M6.4 N45.42 E16.26 Depth: 10.0km ID:us6000d3zh



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

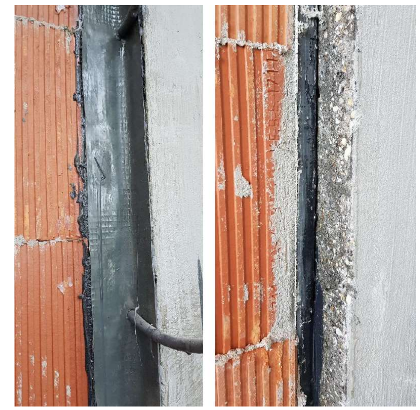
Scale based on Worden et al. (2012) Version 4: Processed 2020-12-30T11:21:46Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Solutions resistant to seismic and strong wind loads causing stress concentration and large deformations

Proven experimentally by shake table tests!

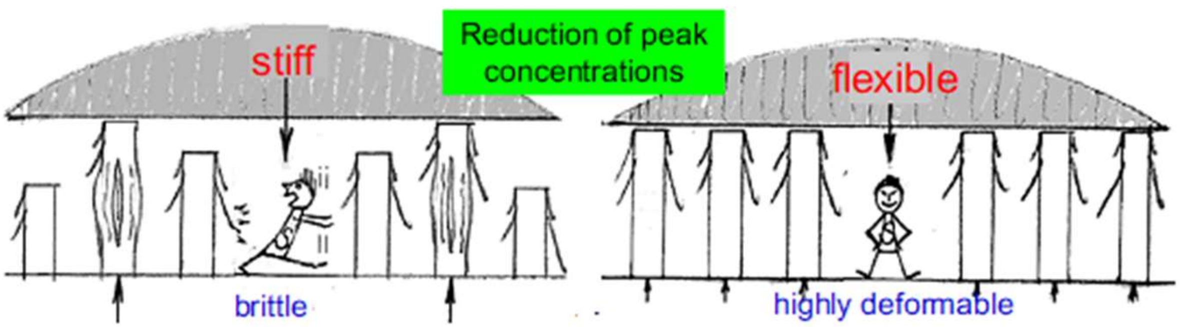
PUFJ - PolyUrethane Flexible Joints

Deformable structural connectors transferring high loads and high deformations



FRPU - Fiber Reinforced PolyUrethanes

Deformable adhesives and composite matrices dissipating energy



stress concentration

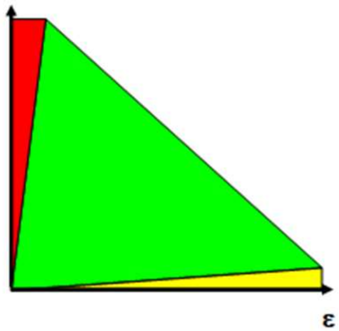
even stress redistribution

JOINTS IN STRUCTURAL ELEMENTS MADE OF BRITTLE MATERIALS

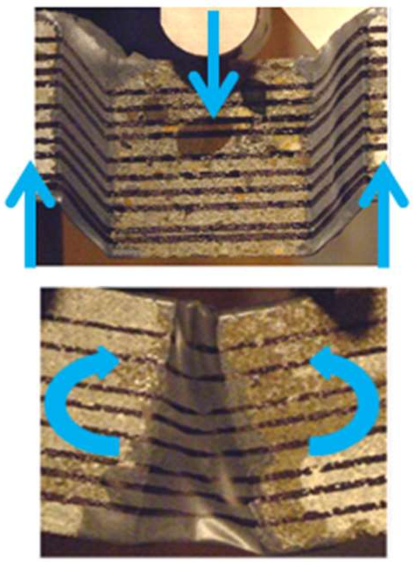
STIFF JOINTS

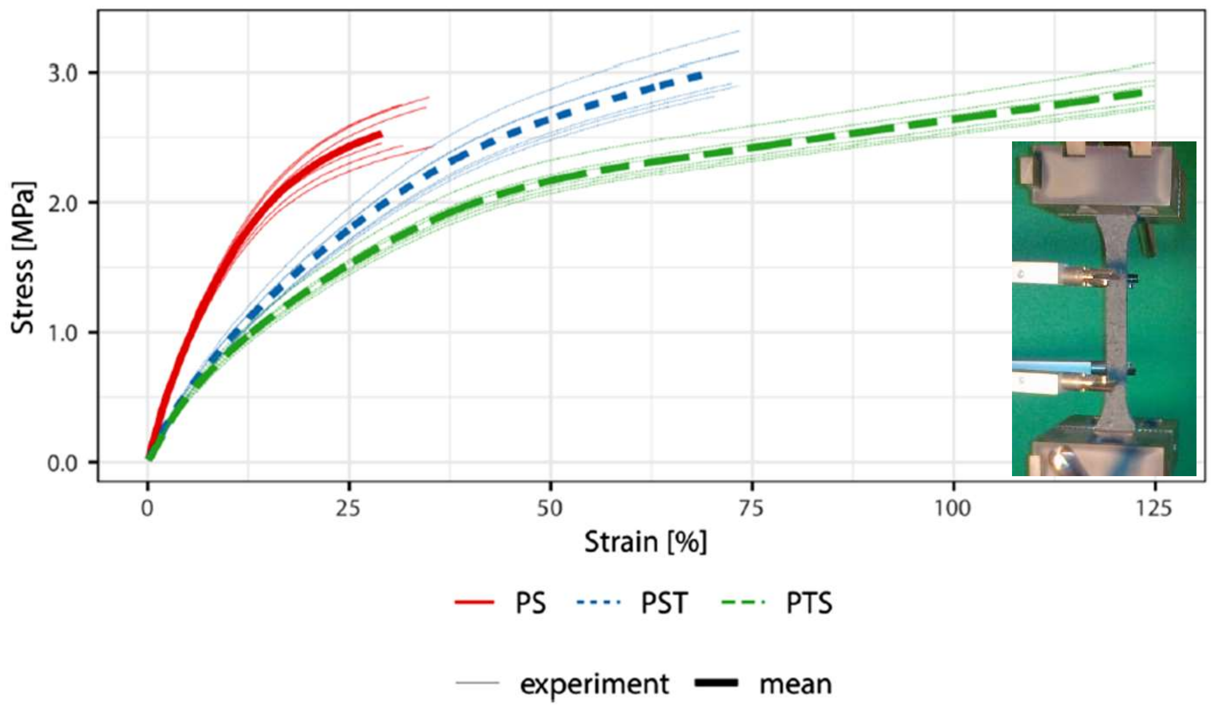
POLYMER FLEXIBLE JOINTS

SEALANTS



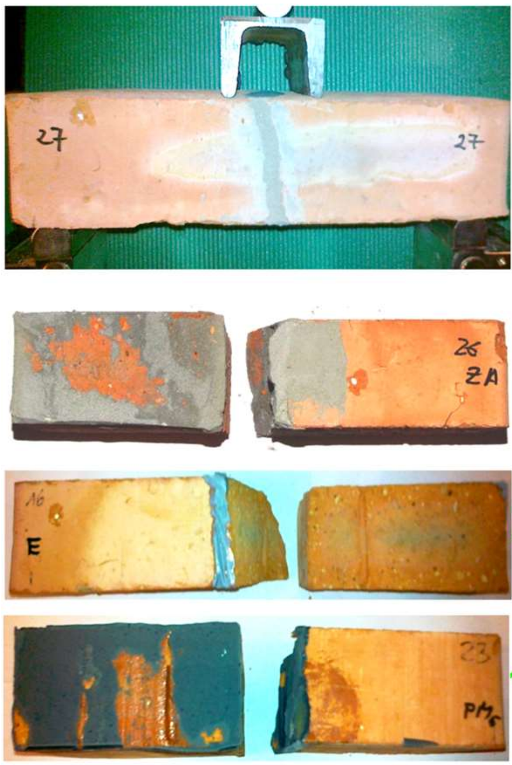
Polyurethanes using for PUFJ and FRPU of non-linear characteristic

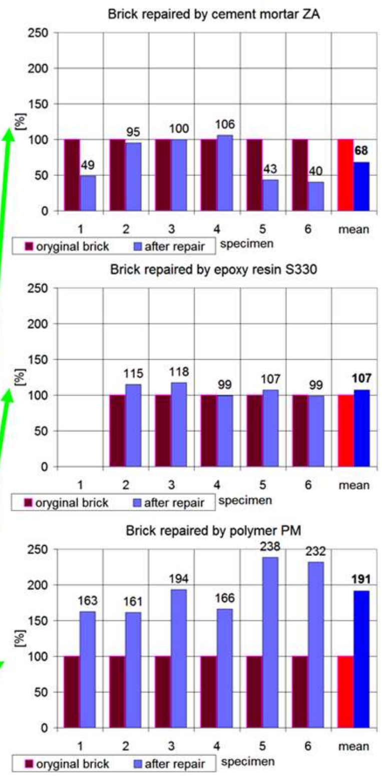


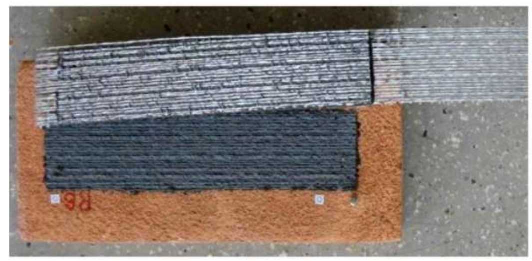


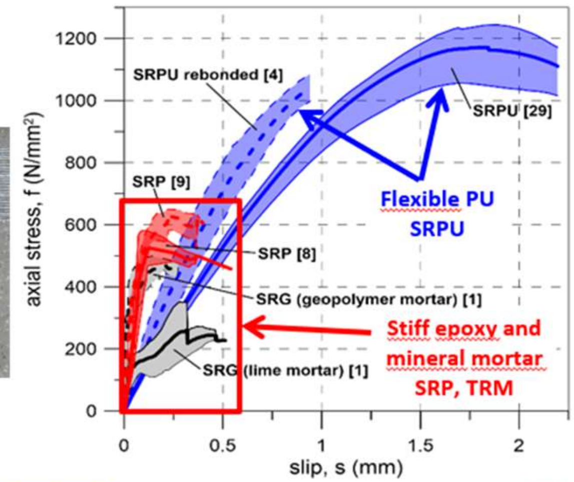
PUFJ and FRPU transfer high loads and large deformations simultaneously

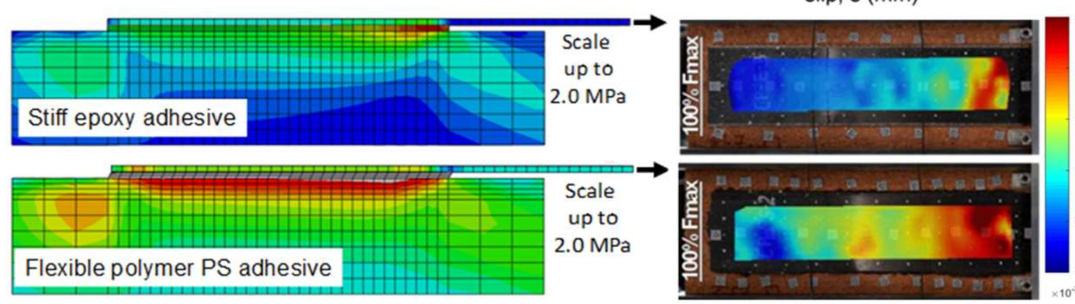
PUFJ and FRPU
(higher bonding effectiveness for weak materials with low strength)









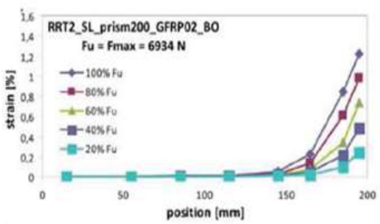


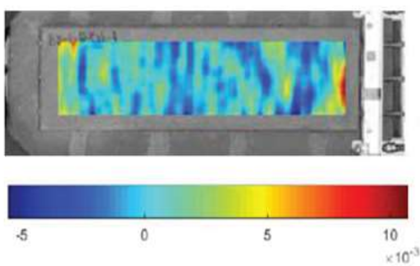
Experimental, analytical, and field research, carried out by international teams of seismic experts

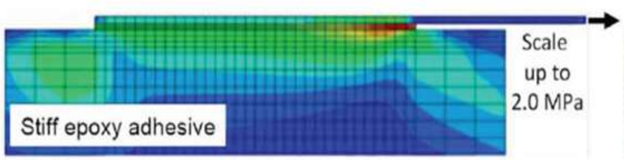
Composite strengthening of masonry element single-lap shear test

- *Stiff or flexible adhesive layer in shear?*

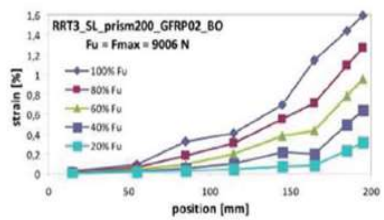
Stiff epoxy adhesive

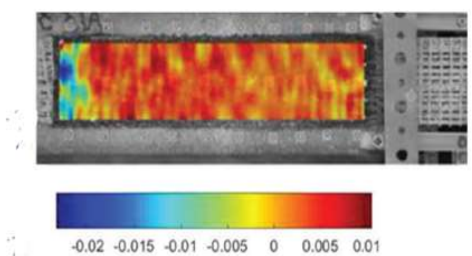


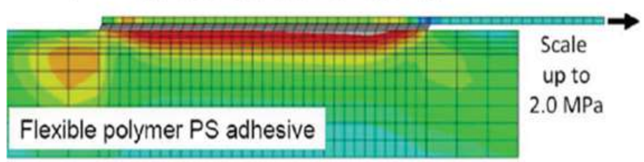


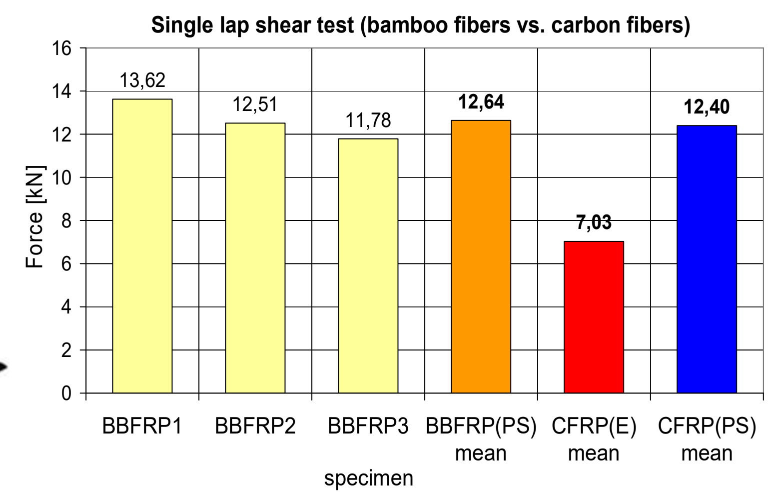


Flexible PU adhesive



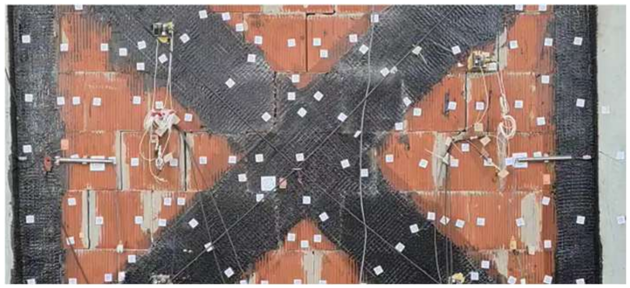






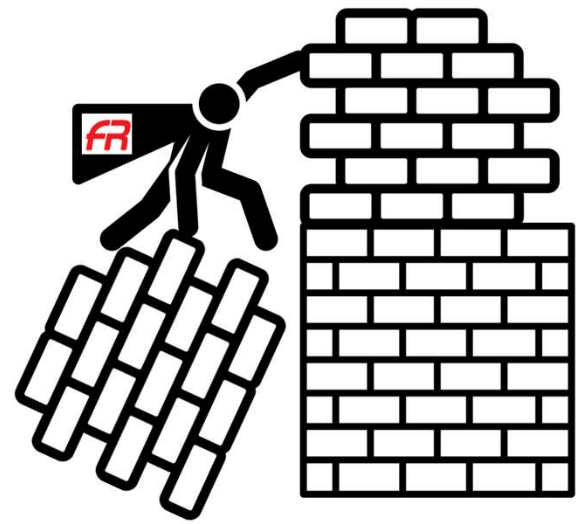
Deformable structural connectors transferring high loads and high deformations

PUFJ



FRPU

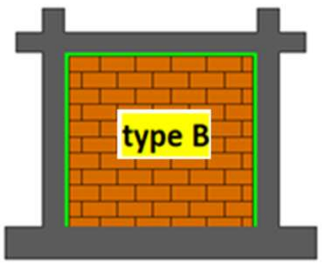
FLEX AND ROBUST SYSTEMS
a way for people to survive natural disasters



Deformable adhesives and composite matrices dissipating energy

EARTHQUAKES AND STRONG WINDS DO NOT KILL PEOPLE, BUILDINGS DO

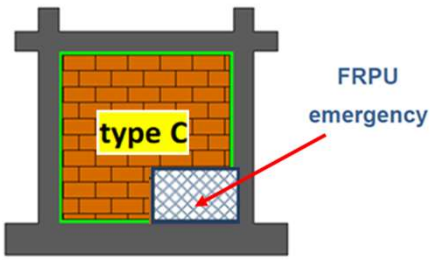
PUFJ injected at 3 edges



Global stiffness decrease 100% --> 6% after in-plane test

PUFJ_IN protected infill against falling out

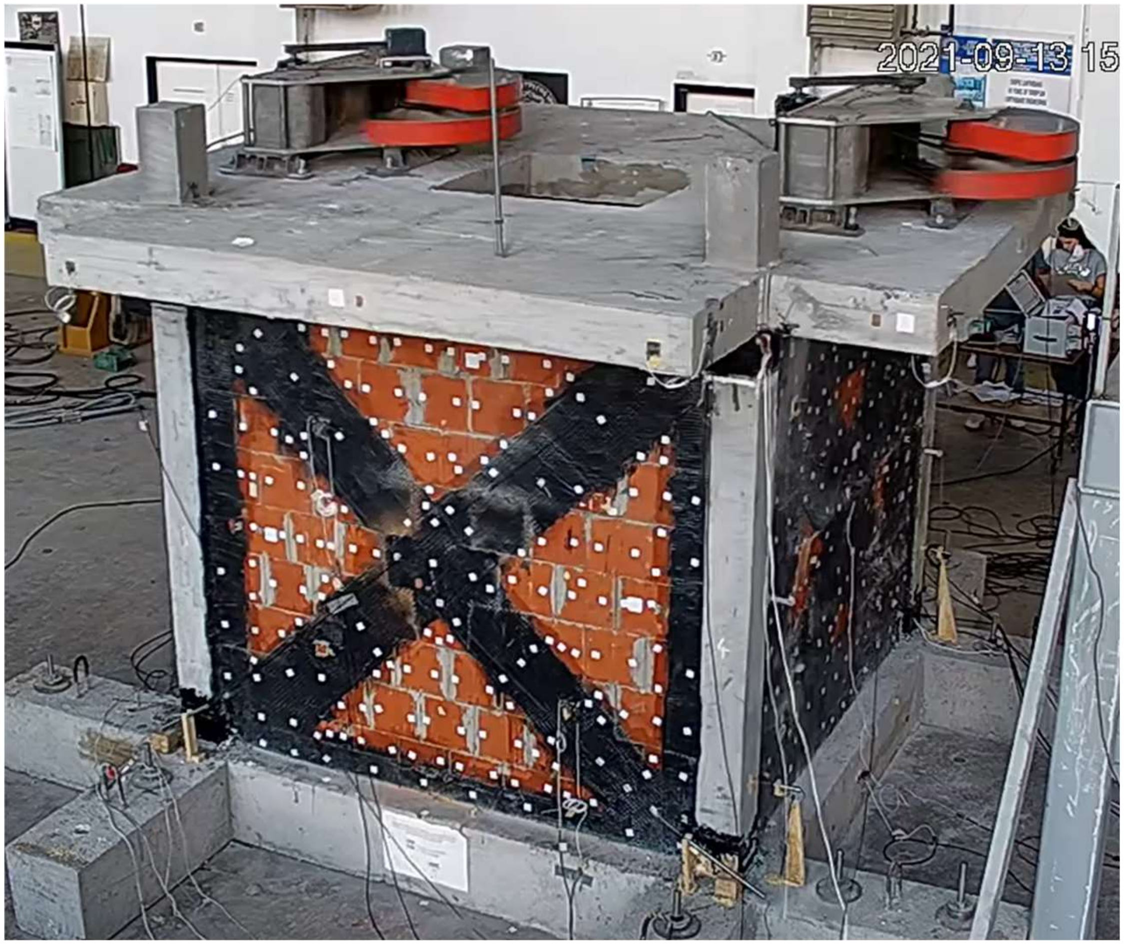
FAR products recovered stiffness and resistance

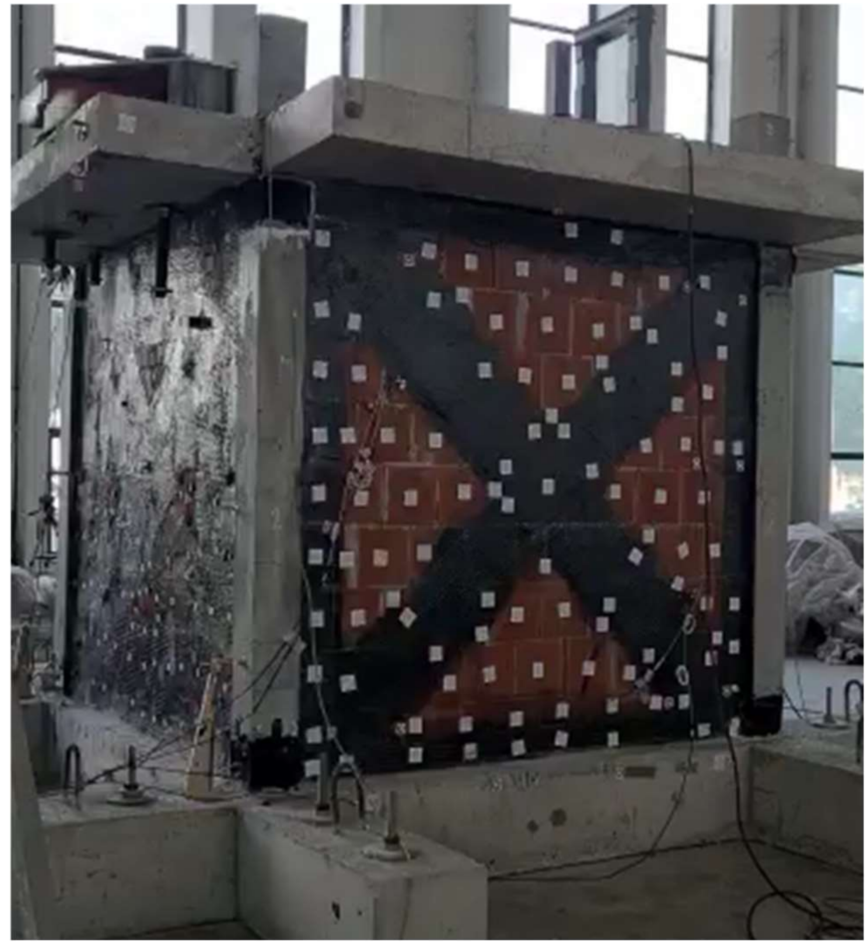


Global stiffness increase
21% --> 77%

PUFJ_PR and FRPU made strong infill

Force vibration test after the shake table tests in IZIIS



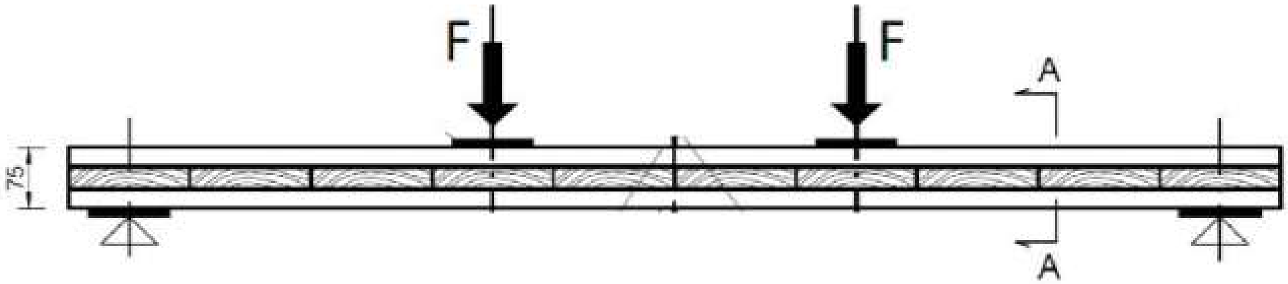


Stress concentrations generated by stiff adhesives

CLT

with stiff PUR

and with flexible PU



Stiff PUR adhesive (one-component)

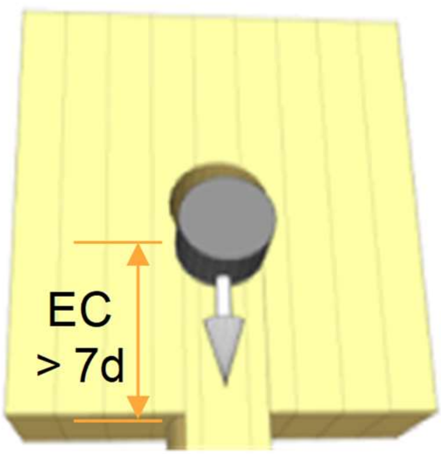
brittle and sudden – stiff adhesives

Flexible PU adhesive (two-component)

ductile and safe – flexible adhesives

Stress concentrations in wooden elements (caused by steel dowels)

Local damage around a steel dowel

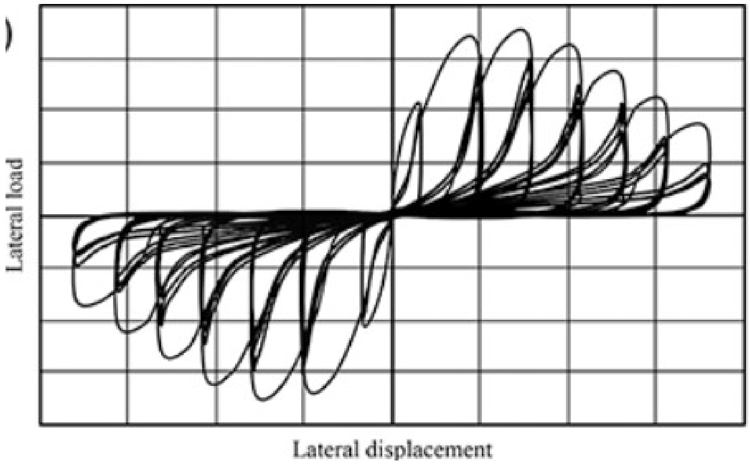


Larsson G.: HIGH CAPACITY TIMBER JOINTS. Proposal of the shear plate dowel joint. Lund University. ISBN 978-91-7753-107-4,

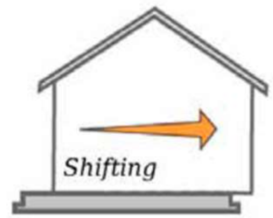
Damage of a timber element caused by a steel dowel

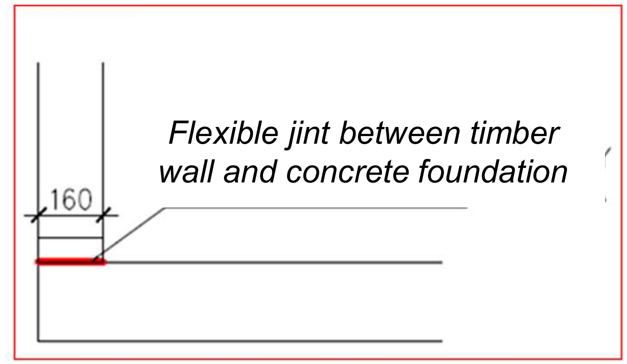
Valluzzi M.R., Garbin E., Modena C., Bozza E., Francescato D.: Modeling of timber floors strengthened with seismic improvement techniques. Wiadomości Konserwatorskie • Journal of Heritage Conservation • 46/2016, pp 69-79,

Resistance to cyclic loads

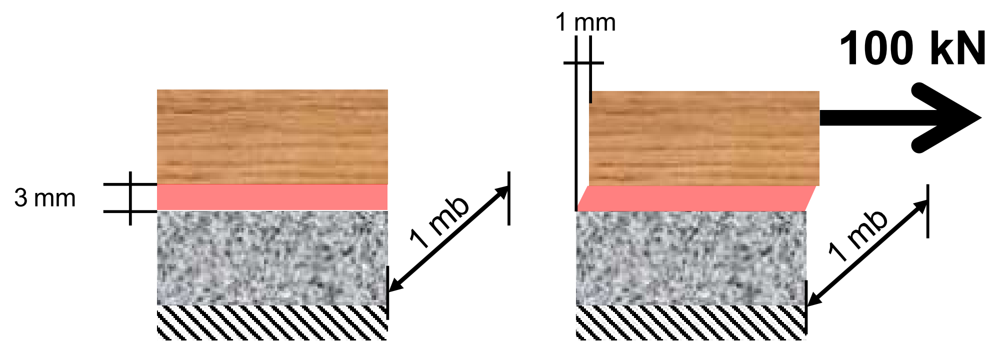


Porcu M.C.: Ductile Behavior of Timber Structures under Strong Dynamic Loads. Chapter 9. Engineering » "Wood in Civil Engineering", book edited by Giovanna Concu, ISBN 978-953-51-2986-8, Print ISBN 978-953-51-2985-1, Published: March 1, 2017

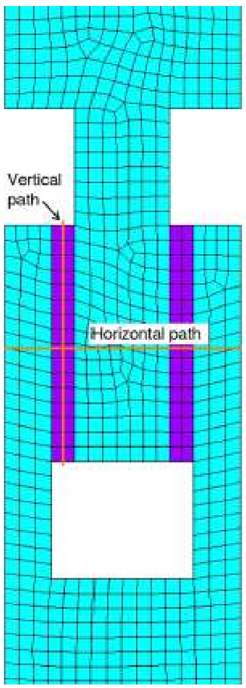


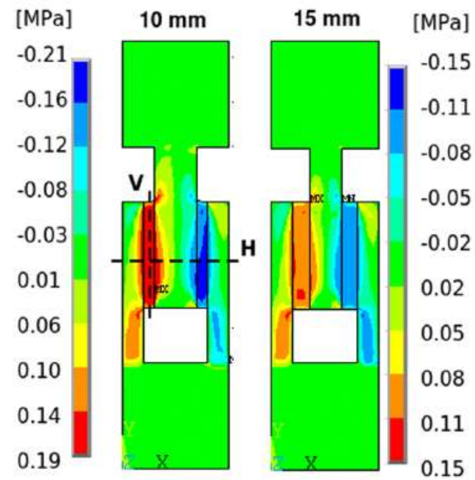


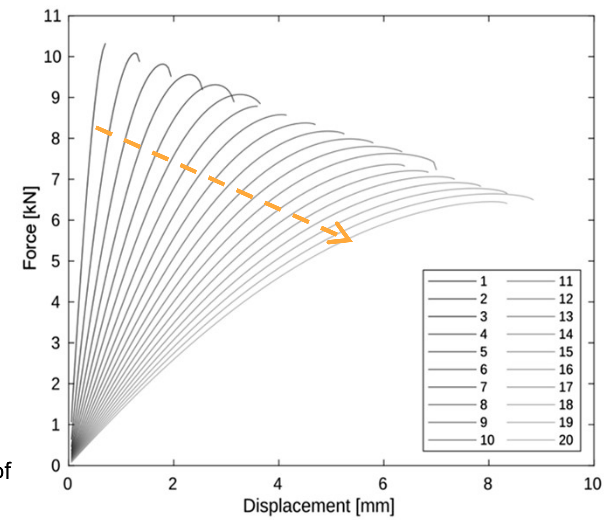
Min-juan H., Hui-fen L.: Comparison of glulam post-to-beam connections reinforced by two different dowel-type fasteners. Construction and Building Materials. Volume 99, 30 November 2015, Pages 99-108



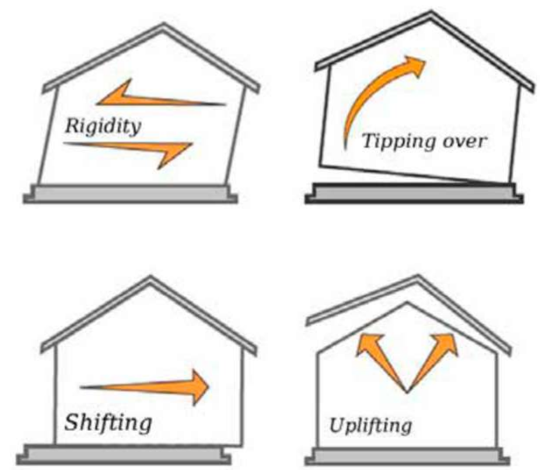
Thickness influence on stiffness and stress distribution in flexible adhesives







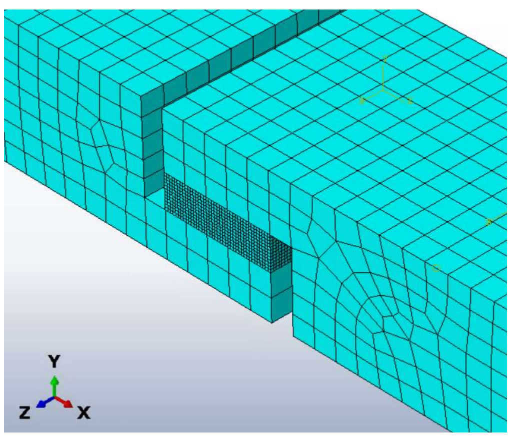
Pečnik J.G., et al.: Mechanical performance of timber connections made of thick flexible polyurethane adhesives. Engineering Structures 247 (2021) 113125, pp. 1-12.



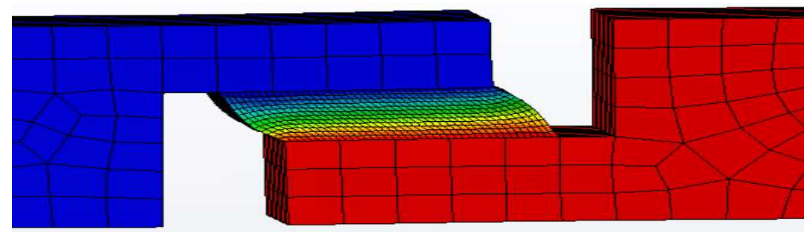
Almost even stress distribution in flexible joint

Shear failure mode

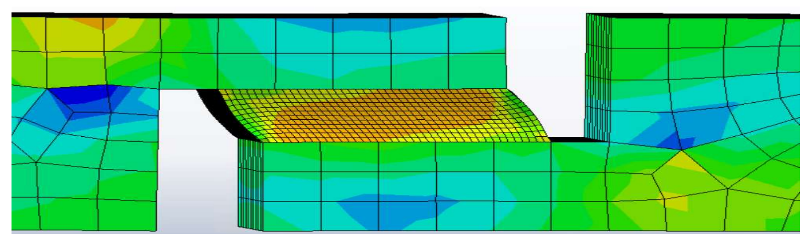
Numerical model



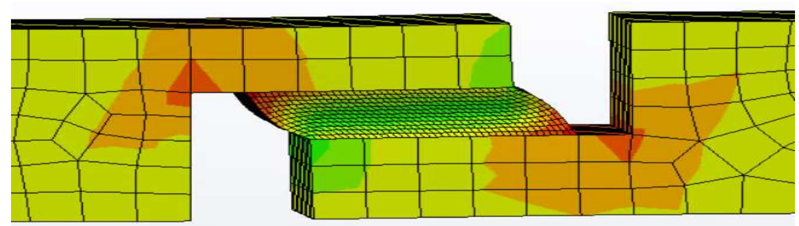
Nonlinear displacement



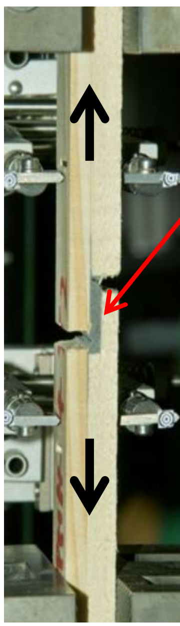
Shear stress



Normal stress

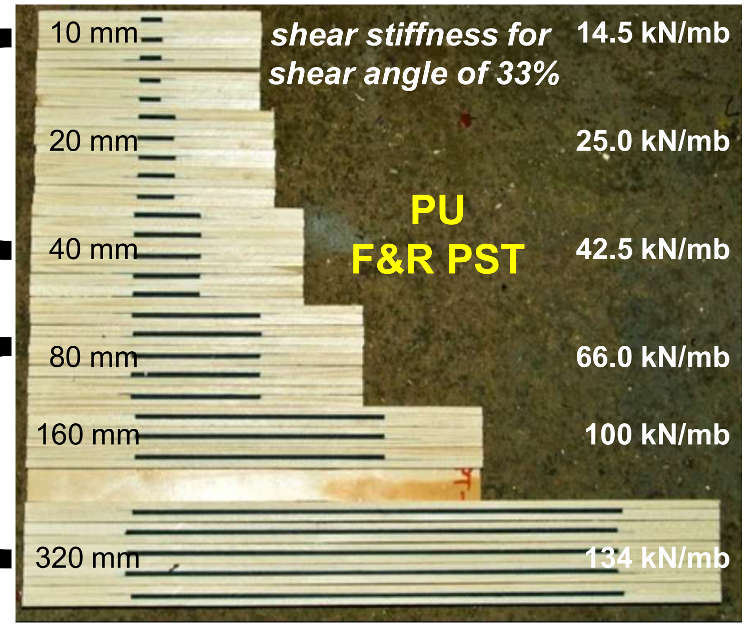


Bonding length influence on load capacity in flexible adhesives



τ_{max} = 2,5 MPa

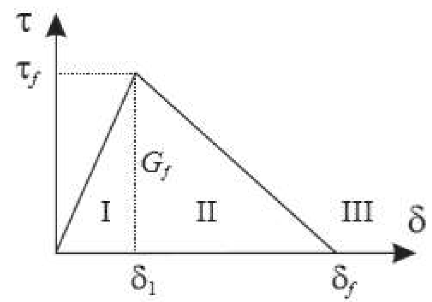
γ_{max} = 100 %

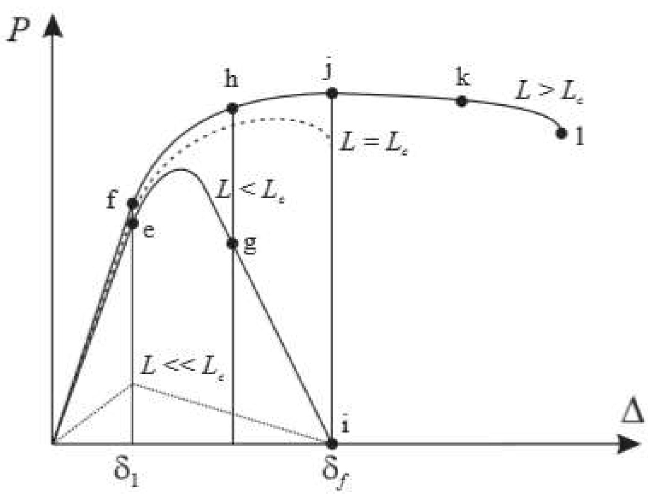


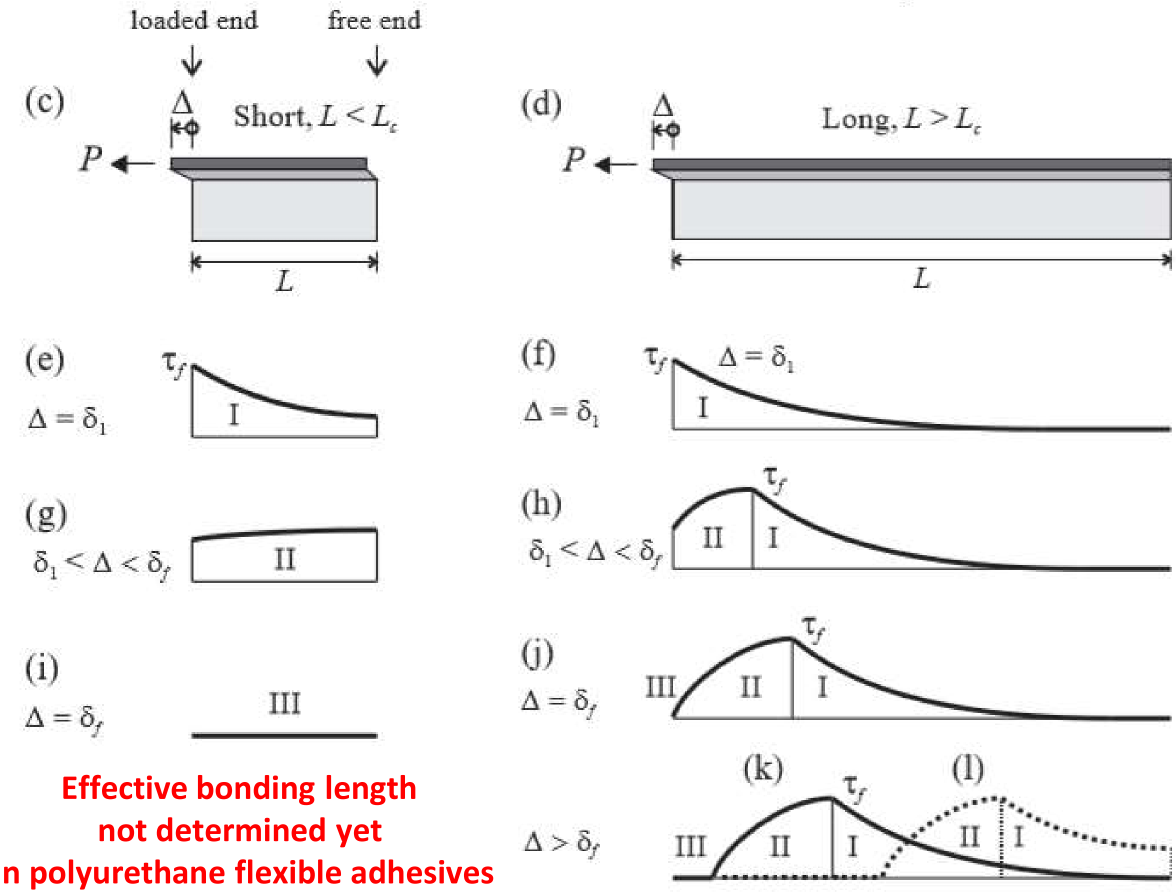
Failure of polymer in short connections

Failure of timber in long connections

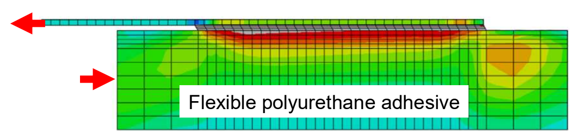
Fracture energy aproach in SLST - effective bonding length [Le] (detachment phenomenon)

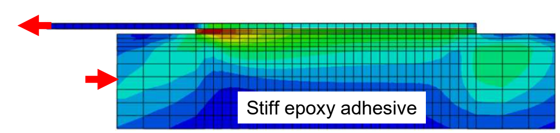






Effective bonding length not determined yet in polyurethane flexible adhesives

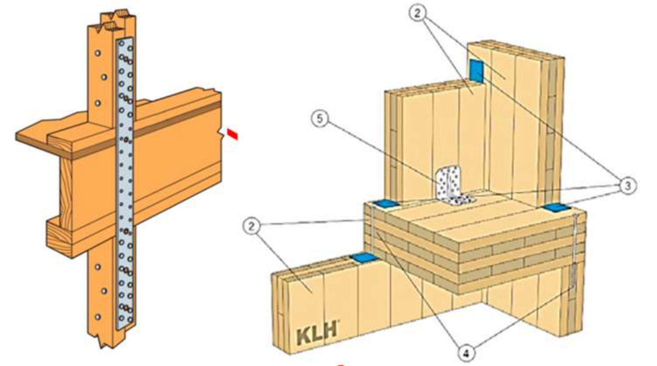


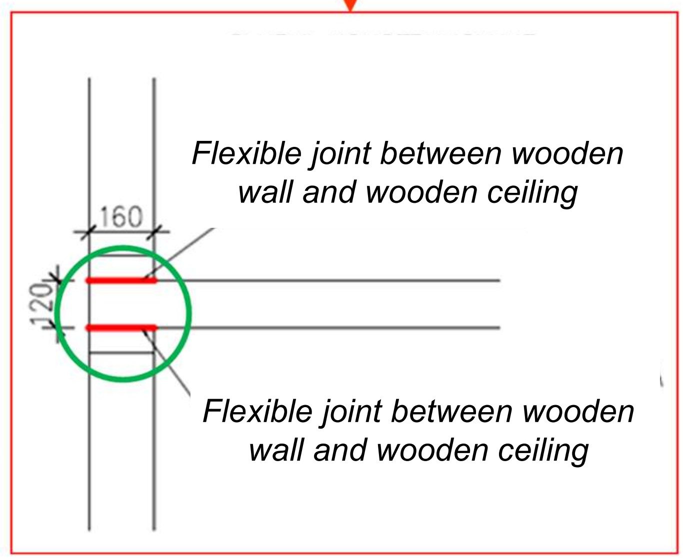


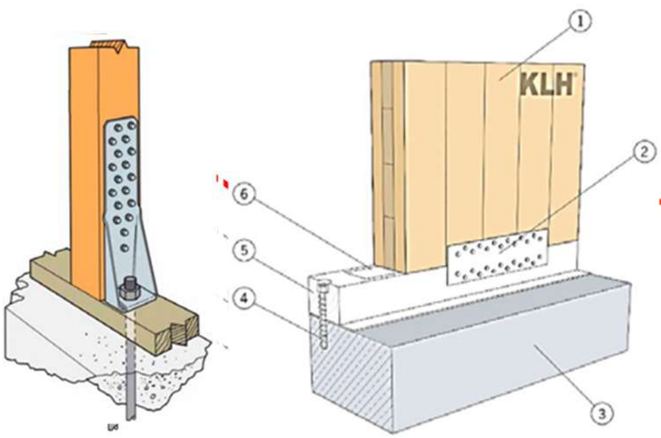
Hybrid connections: steel dowels - flexible polyurethane adhesives

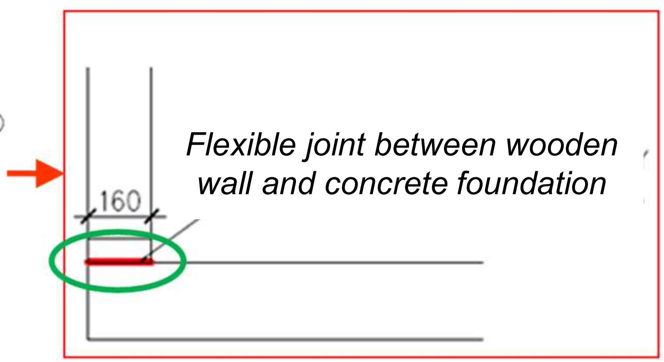
New flexible polyurethane adhesive:

- *blocks the transfer of moisture and thermally insulates from the ground*
- *enables quick assembly and disassembly (by a saw) of elements made of various materials*
- *ensures tightness of connections along their entire length*
- *ensures stability of deformation properties under cyclic loads*

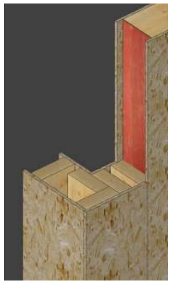


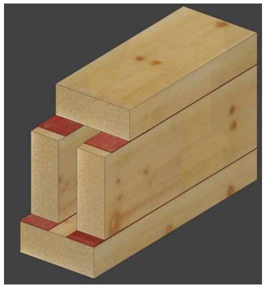






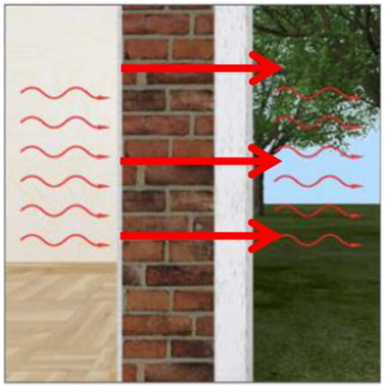
Prefabricated timber houses with PUFJ (injected and prefabricated)





Hydro-thermal protection against vapor and heat transfer

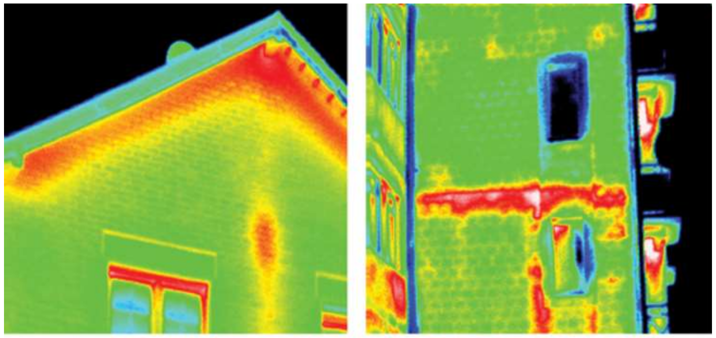
Vapor and heat transfer



Polyurethane F&R PM - vapor barrier (can protect wood)

- water vapor permeability $w_p = 7.38 \cdot 10^{-11}$ kg/($m^2 \cdot s \cdot Pa$)
- water vapor diffusion resistance factor μ = 294

Thermal video camera



Avoiding of thermal bridges

Material samples	Thermal conductivity coefficient λ [W/(mK)]	The volume heat capacity x 10^3 C_v [kJ/(m^3K)]
Wood	0.1157	1.3595
PM soft polymer	0.1013	0.7418

MEZeroE project - virtual market place for innovative products in nZEB envelopes

HORIZON 2020

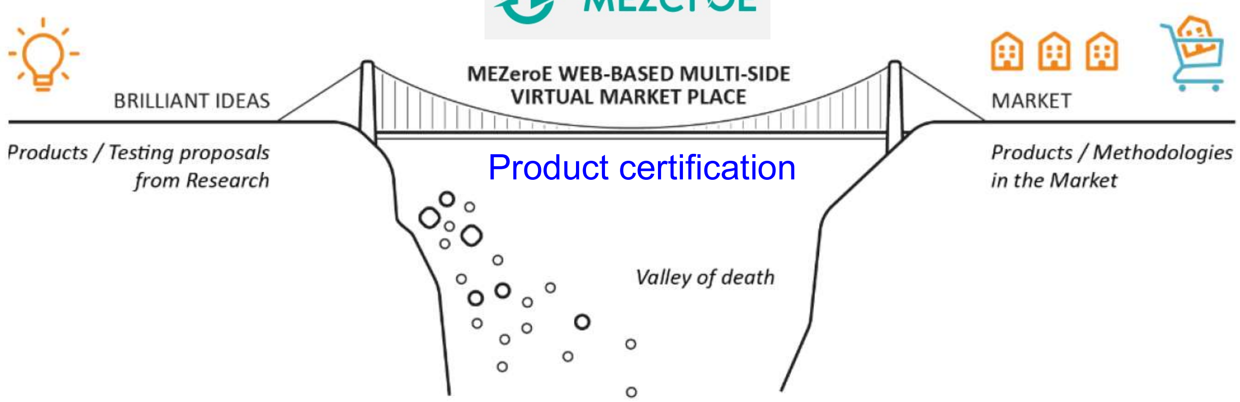
Measuring Envelope products and systems contributing to next generation of healthy nearly Zero Energy Buildings

EUROPEAN COMMISSION
Directorate-General for Research and Innovation
RTD.F – Prosperity
F.4 – Materials for Tomorrow

Technical requirements	Requirements categories under EU Regulation 305/11	Requirements implementation
Safety	Mech. resistance and stability	Statics, durability, Seismic resistance
	Safety in case of fire	Reaction to fire, fire resistance, propagation
	Safety and accessibility in use	Building as a safe to use system
Health	Hygiene, health, environment	High IEQ, water tightness, vapour permeability
	Protection against noise	Airborne sound insulation, soundscape, vibration
Efficiency	Energy economy, heat retention	nZEB, SRI, air permeability
	Sustainable use of nat. sources	GPP, envelope circular economics

https://www.mezeroe.eu/

MEZEROE



MEZeroE

Measuring Envelope systems for Zero Energy buildings

SERVICE PROVIDERS

eurac research
POLITECNICO MILANO 1863
LEITAT managing technologies
universität innsbruck
ZAG
Cracow University of Technology
ITeC
Danmarks Tekniske Universitet DTU
tecnalia
compáz

INDUSTRIAL PARTNERS

FOCCHI SINCE 1914
VELUX
WindowMaster Fresh Air. Fresh People.
Flexbrick dressing architecture
Heliatek INDEPENDENT. GREEN. FUTURE.
TECNAN TECNOLOGIA NAVARRA DE NANOPRODUCTOS S.L.
FLEX AND ROBUST SYSTEMS
rothoblaas Solutions for Building Technology
RIKO Riko Hiše
INDRESMAT INDUSTRIAL RESINS & MATERIALS
arbnco
greenTEG
Nuvap
Pellini

MEZeroE project is a project receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 953157.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Measuring Envelope systems for Zero Energy buildings
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OPEN INNOVATION DIGITAL PLATFORM FOR ZERO ENERGY BUILDING ECOSYSTEM
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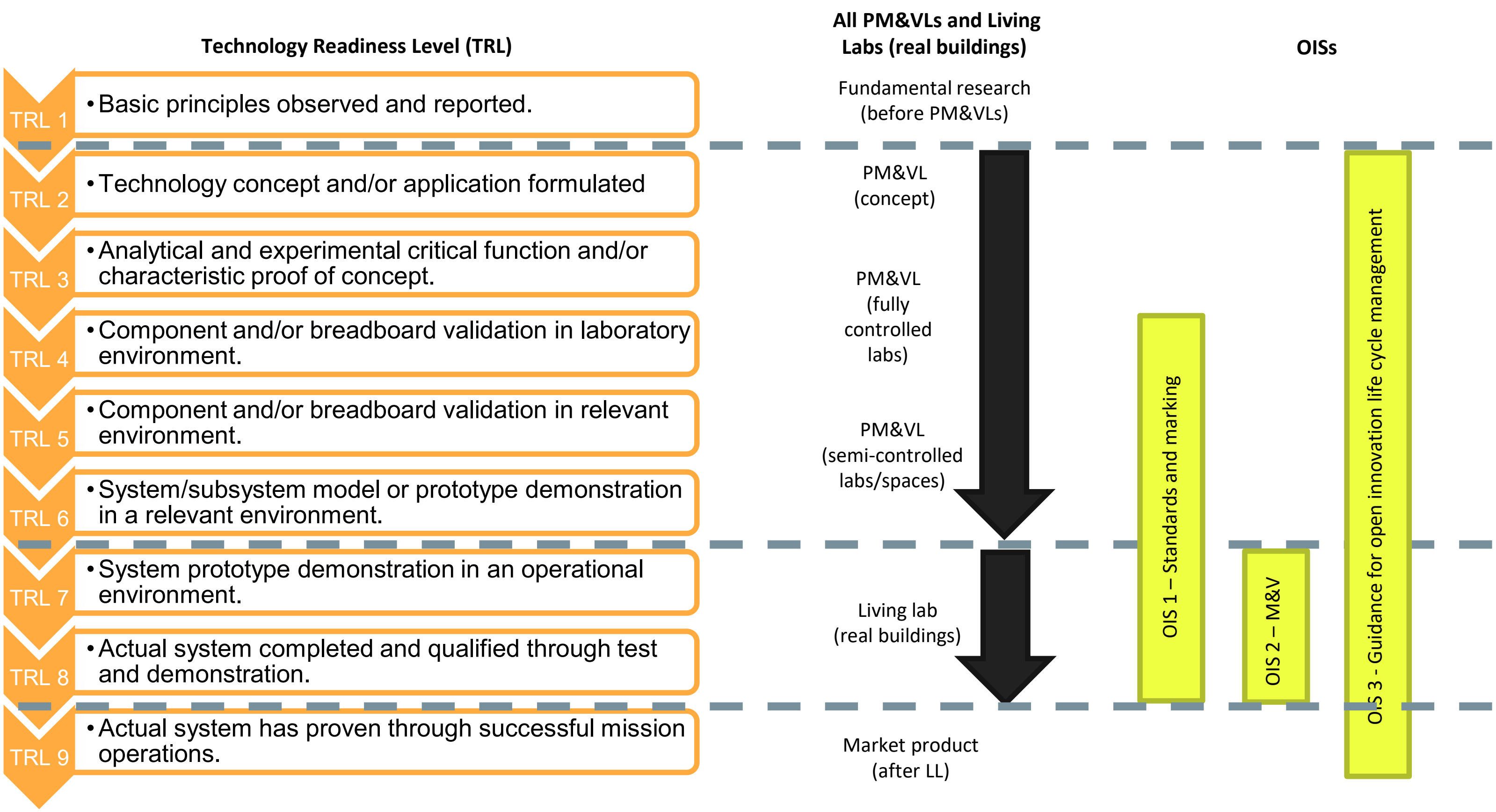
Procedure steps at the MEZeroE platform



MEZeroE

Pilot Measurements & Verification Lines (PM&VL)

PMVL1
Safety, performance and efficiency characterization of BIPV and hybrid PV/T systems

This line is dedicated to photovoltaic and hybrid photovoltaic/thermal modules. It allows the measurement of their performances in controlled lighting conditions by using a sun simulator and by recording results at different angles of incidence. It makes it possible to measure modules in real outdoor conditions and to contrast them with the indoor equivalents, which allows the closest possible predictive data. With PMVL 1, the behavior of these modules can also be tested in case of fires that might occur because of an overheat or a default in the electrical system. With a focus on the safety of the occupants, it indicates how the modules and their components (glass, polymers, etc.) will behave when they burn. Potential risks – burning residue from melting polymers, breaking glass, electrical arcs, etc. – can be assessed and remedied.

PMVL 2
Building envelope/IEQ (Indoor Environmental Quality) interaction facing health requirements

This line has been designed to measure the performance of a façade building element (including windows) to measure its U-value performance, which refers to its capacity to keep or transmit heat flow and its insulating capability. It can also measure the acoustic performance of the façade elements. By quantifying these thermal and acoustic performances, it leads to solutions that offer more comfort to a building's occupants. In addition, this line is equipped to make chemical analyses of the organic volatiles, with their potential health risks, that can be emitted by these materials.

PMVL 3
Reliability of BIPV products, using accelerated tests for stability and quality of materials/products for outdoor use

This pilot line complements PMVL 1. It provides an infrastructure to test BIPV systems in conditions which replicate – to the greatest extent possible – their real-world equivalents. It allows our industrial partners to understand how their PV products will behave over the years in terms of electrical efficiency, based on how and where they are installed in a building.

PMVL 4
Dynamic glass systems facing efficiency requirements. A set of experimental and analytical tools to validate the performance of newly developed dynamic glazing elements

This pilot line is dedicated to window manufacturers. It makes it possible for them to understand precisely how their dynamic glass will behave in terms of light comfort and the insulation properties of the glass. It also ensures that these characteristics align with international standards.

PMVL 5
Building/user interaction characterization facing efficiency requirement

This line is squarely focused on IoT and AI tools that could be introduced in support of the occupants' comfort. It is designed to assess and control certain parameters of the quality of the indoor environment and the behavior of the inhabitants.

PMVL 6
Multilayer dry nEESs (nZEB Enabler Envelope Solutions) characterization facing Health and Safety requirement

This line provides an infrastructure to test materials at different scales. Considering the material itself, it offers, for example, an understanding of its resistance to impact. But it also makes it possible to examine – on a large scale – entire façade elements with tests that are ever-closer to the conditions they will face in the real world. From this series of measurements, some predictive modelling can be calculated and offered as important feedback for the manufacturers, helping them to improve their products.

PMVL 7
Testing of connections in envelopes

This line is specialized in testing the connection or adhesion between two different materials like, for example, the glue between two layers in a sandwich panel, the glue inside a PV module, or a window joint. Among other things, it tests the solidity of a glue and its intrinsic properties while aging, which helps us understand how these crucial elements will behave and last throughout the years.

PMVL 8
Enables a full-scale performance evaluation of the thermal and optical characteristics as well as comfort criteria of transparent, multi-functional facade elements

The PMVL 8 line is focused on testing transparent materials like window and glass façade elements. It has been conceived to evaluate the thermal and visual performances and comfort of the people living and working inside the building.

PMVL 9
Fire safety, hygro-thermal and acoustic characterisation of wooden-based prefab façade systems

This line, which is specifically dedicated to wood-based materials, tests their behavior when they are exposed to fire and humidity. It also considers the occupants' exposure to sound and to the acoustic characteristics of the materials.

FLEX AND ROBUST SYSTEMS

Item	Leading partner
PM&VL1	Tecnalia
PM&VL2	Eurac
PM&VL3	Leitat
PM&VL4	Leitat
PM&VL5	DTU
PM&VL6	PoliMI
PM&VL7	CUT
PM&VL8	UIBK
PM&VL9	ZAG

PM&VL7 | CUT

Cracow University of Technology

Tested product

Initial testing before ageing (durability tests)

(7.1) Mechanical testing
- test line 1
- test line 2
  - test line 2a
- ....

(7.3) Vibro-acoustic testing
- test line 1
- test line 2
  - test line 2a
- ....

(7.4) Thermal testing
- test line 1
- test line 2
  - test line 2a
- ....

(7.2) Durability tests (ageing): environmental, chemical, biological, mechanical
- test line 1
- test line 2
  - test line 2a
- ....

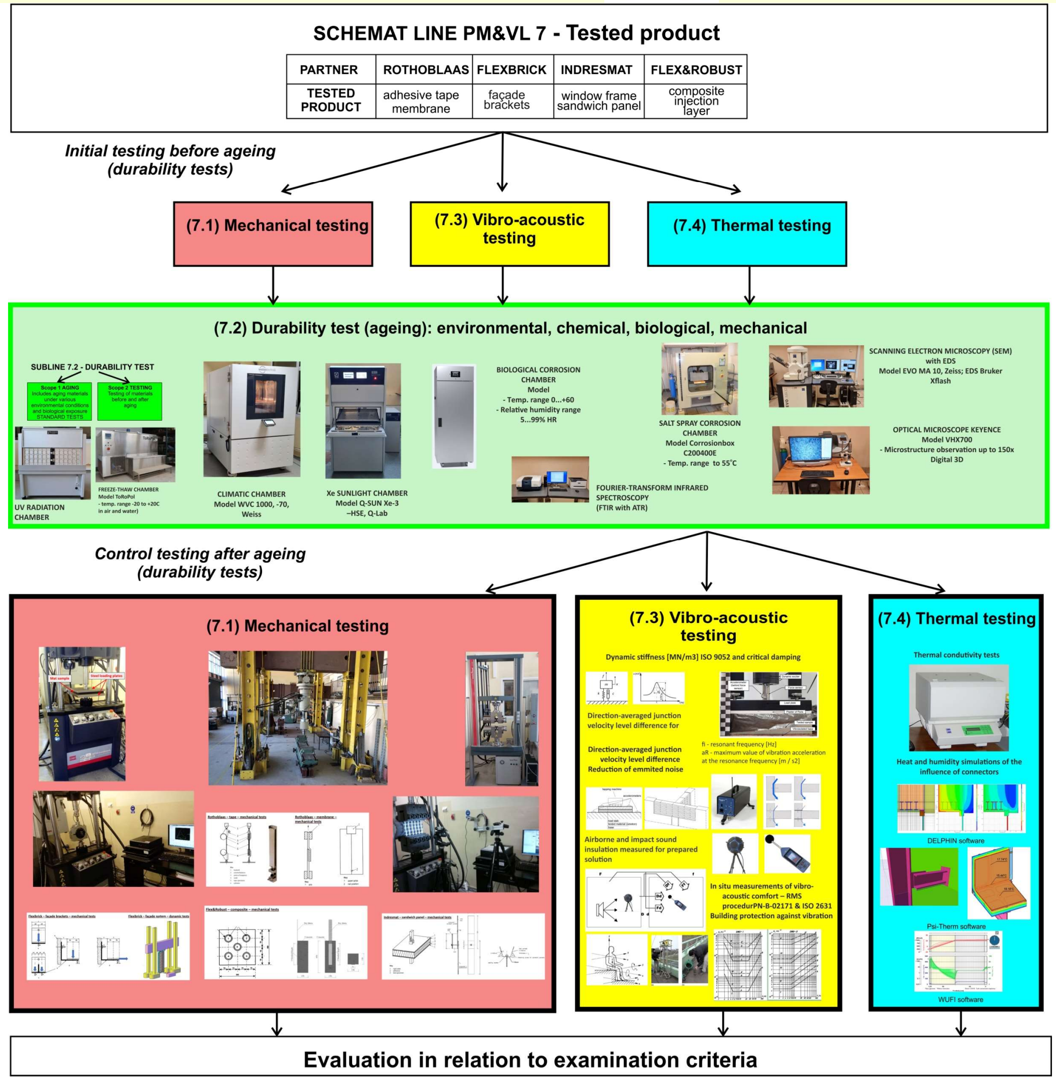
Control testing after ageing (durability tests)

(7.1) Mechanical testing
- test line 1
- test line 2
  - test line 2a
- ....

(7.3) Vibro-acoustic testing
- test line 1
- test line 2
  - test line 2a
- ....

(7.4) Thermal testing
- test line 1
- test line 2
  - test line 2a
- ....

Evaluation in relation to examination criteria



Symbol	Product	Subline	Test	WP3.4*
FRC	Flex&Robust composite	(7.1)	Breaking force /reference mechanical test before artificial aging/glass fibre grid	12
		(7.1)	Matrix tensile strength and modulus of elasticity /reference mechanical test before artificial aging/ polyurethane PS	2
		(7.1)	Composite tensile strength and modulus of elasticity - warp direction /reference mechanical test before artificial aging/ PS reinforced with glass fibre grid	4
		(7.2)	Artificial ageing behaviour before durability test - Observation in optical microscope and in scanning microscope SEM	22 i 23
		(7.2)	Artificial ageing behaviour before durability test - Testing FTIR	24
		(7.2)	Durability - sunlight Xe	19
		(7.1)	Mechanical test after artificial ageing - Breaking force - glass fibre grid	12
		(7.1)	Mechanical test after artificial ageing -Matrix tensile strength and modulus of elasticity polyurethane PS	2
		(7.1)	Mechanical test after artificial ageing -Composite tensile strength and modulus of elasticity - warp direction PS reinforced with glass fibre grid	4
		(7.2)	Artificial ageing behaviour after durability test - FTIR	24
		(7.2)	Artificial ageing behaviour after durability test - Observation in optical microscope or in scanning microscope SEM	22 i 23
		(7.2)	Durability - see water or breeze	18
		(7.1)	Mechanical test after artificial ageing -Composite tensile strength and modulus of elasticity - warp direction PS reinforced with glass fibre grid	4
		(7.1)	Dynamic stiffness /modulus of composite - warp direction	15
		(7.3)	Critical damping ratio [%]	25
		(7.3)	Dynamic stiffness (MN/m3)	28
		(7.3)	Airborne and impact sound insulation measured for prepared solution	26
		(7.3)	Direction-averaged junction velocity level difference for connector or for connection model	27
		(7.4)	Water vapour diffusion (Interstitial water vapor condensation risk and intensity);	29
		(7.4)	Internal surface temperature	30
		(7.4)	Linear thermal transmittance (iii)	31

Tested Flex&robust Composite in PM&VL_7

Flex&Robust Composite
FRPU – Fiber Reinforced PU
(Fibers in PU matrix)

Tests Flex&robust Injection in PM&VL_7

Symbol	Product	Subline	Test	WP3.4*
FRI	Flex&Robust injection	(7.1)	Initial shear strength	9
		(7.2)	Artificial ageing behaviour before durability test - Observation in optical microscope and in scanning microscope SEM	22 i 23
		(7.2)	Artificial ageing behaviour before durability test - Testing FTIR	24
		(7.2)	Durability - sunlight Xe	19
		(7.2)	Artificial ageing behaviour after durability test - FTIR	24
		(7.2)	Artificial ageing behaviour after durability test - Observation in optical microscope or in scanning microscope SEM	22 i 23
		(7.3)	Critical damping ratio [%]	25
		(7.3)	Dynamic stiffness (MN/m3)	28
		(7.3)	Airborne and impact sound insulation measured for prepared solution	26
		(7.3)	Direction-averaged junction velocity level difference for connector or for connection model	27
		(7.4)	Water vapour diffusion (Interstitial water vapor condensation risk and intensity);	29
		(7.4)	Internal surface temperature	30
		(7.4)	Linear thermal transmittance (iii)	31

Flex&Robust Injection

PUFJ - PU Flexible Joint

(Injected PU)

Tests Flex&robust Layer in PM&VL_7

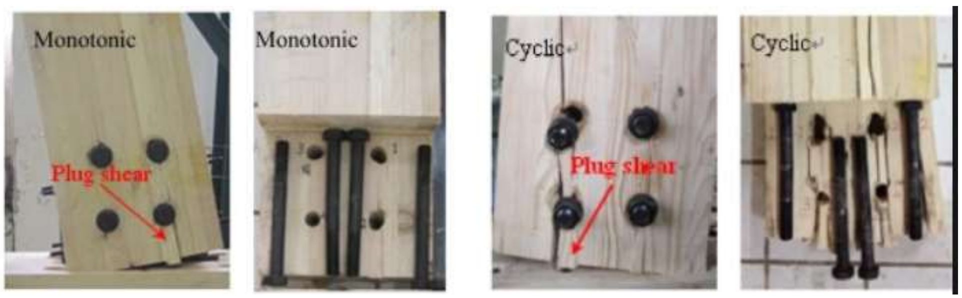
Symbol	Product	Subline	Test	WP3.4*
FRL	Flex&Robust layer	(7.1)	Tensile strength and modulus of elastiicity /reference mechanical test before artificial aging/	11
		(7.2)	Artificial ageing behaviour before durability test - Observation in optical microscope and in scanning microscope SEM	22 i 23
		(7.2)	Artificial ageing behaviour before durability test - Testing FTIR	24
		(7.2)	Durability - sunlight Xe	19
		(7.1)	Mechanical test after artificial ageing - Tensile strength and modulus of elastiicity	11
		(7.2)	Artificial ageing behaviour after durability test - FTIR	24
		(7.2)	Artificial ageing behaviour after durability test - Observation in optical microscope or in scanning microscope SEM	22 i 23
		(7.3)	Critical damping ratio [%]	25
		(7.3)	Dynamic stiffness (MN/m3)	28
		(7.3)	Airborne and impact sound insulation measured for prepared solution	26
		(7.3)	Direction-averaged junction velocity level difference for connector or for connection model	27
		(7.4)	Water vapour diffusion (Interstitial water vapor condensation risk and intensity);	29
		(7.4)	Internal surface temperature	30
		(7.4)	Linear thermal transmittance (iii)	31

Flex&Robust Layer
PUFJ - PU Flexible Joint
(Prefabricated PU)

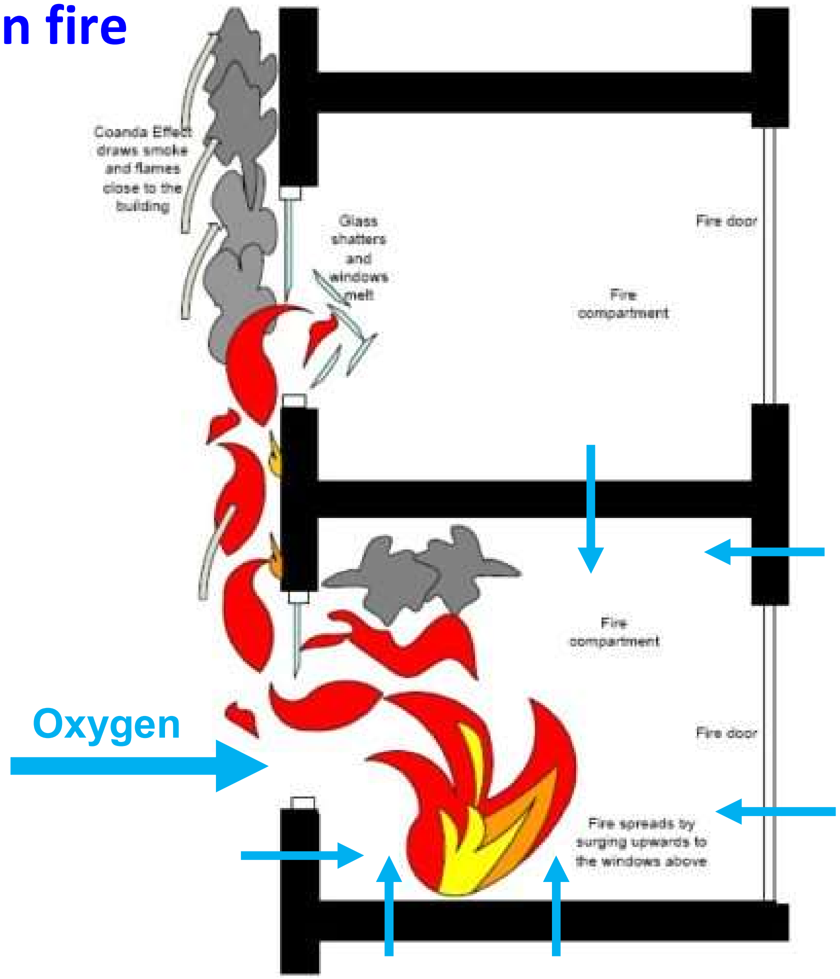
Lack of tightness – problem in fire

Injected

Prefabricated

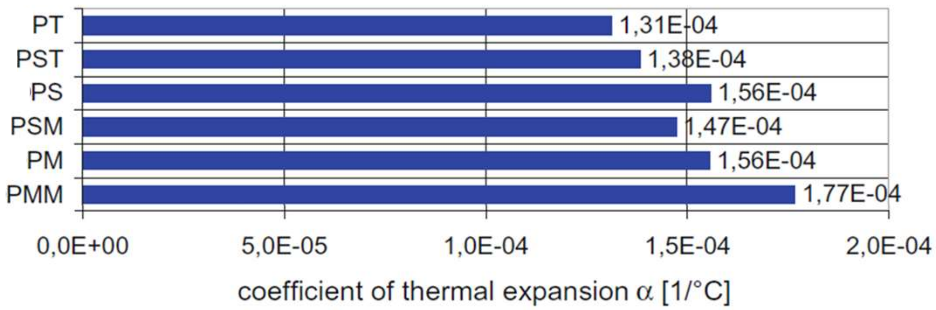


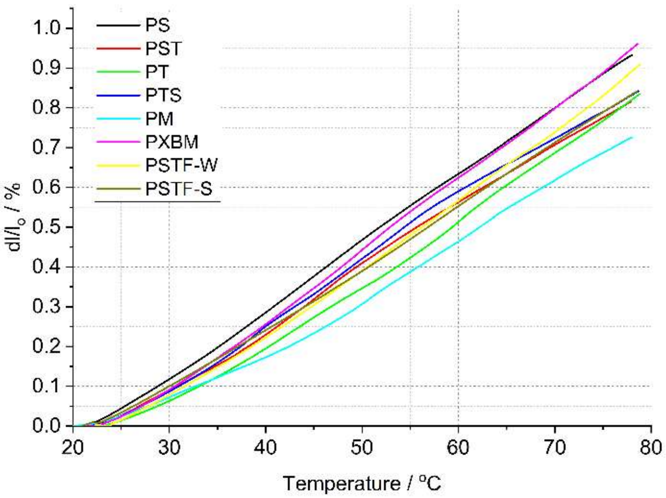
Min-juan H., Hui-fen L.: Comparison of glulam post-to-beam connections reinforced by two different dowel-type fasteners. Construction and Building Materials. Volume 99, 30 November 2015, Pages 99-108



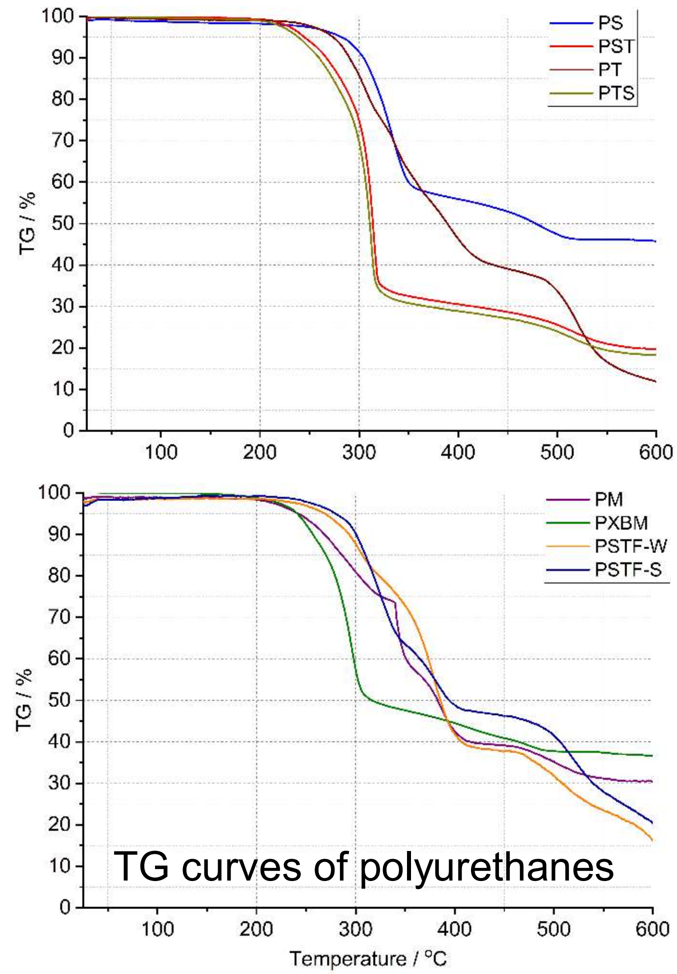
http://pensher-skytech.com/opinion-piece-grenfell-tower/

Thermal stability of flexible (polyurethane F&R P) adhesives



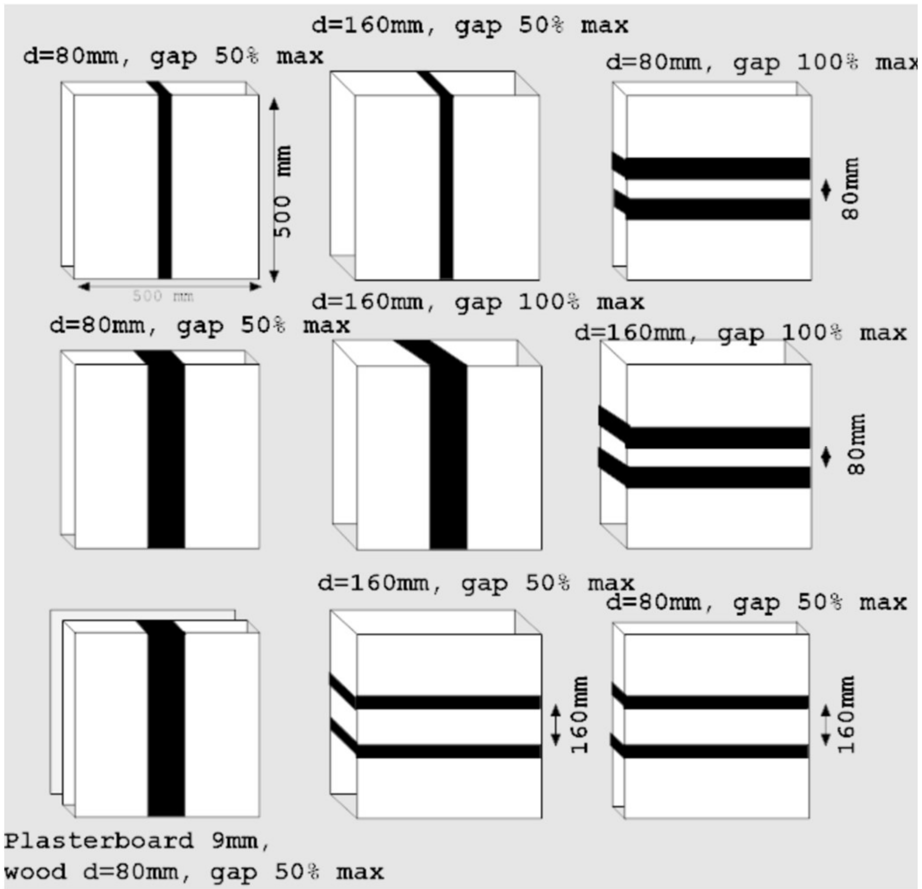


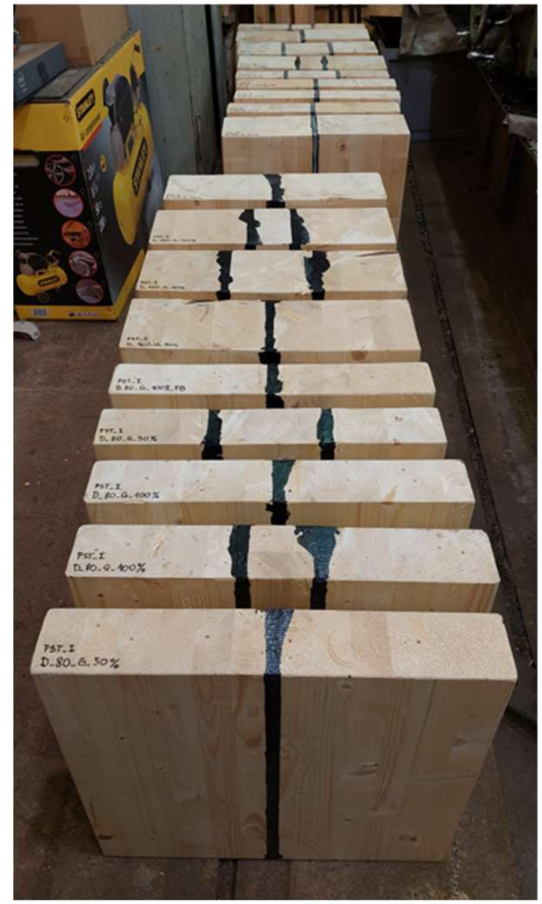
Linear thermal expansion of polyurethanes in elevated temperatures



TG curves of polyurethanes

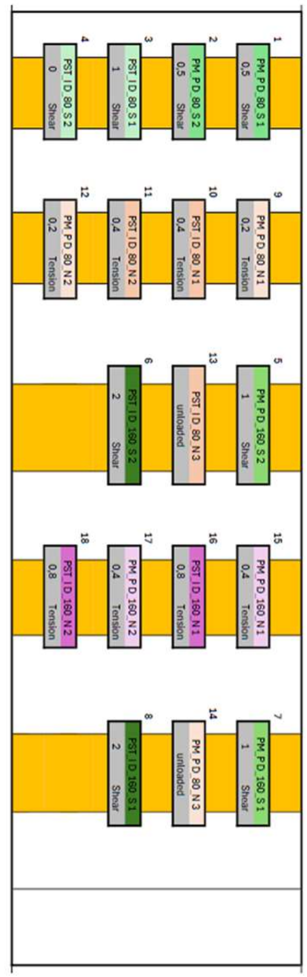
Timber specimens with polyurethane flexible adhesives tested in fire



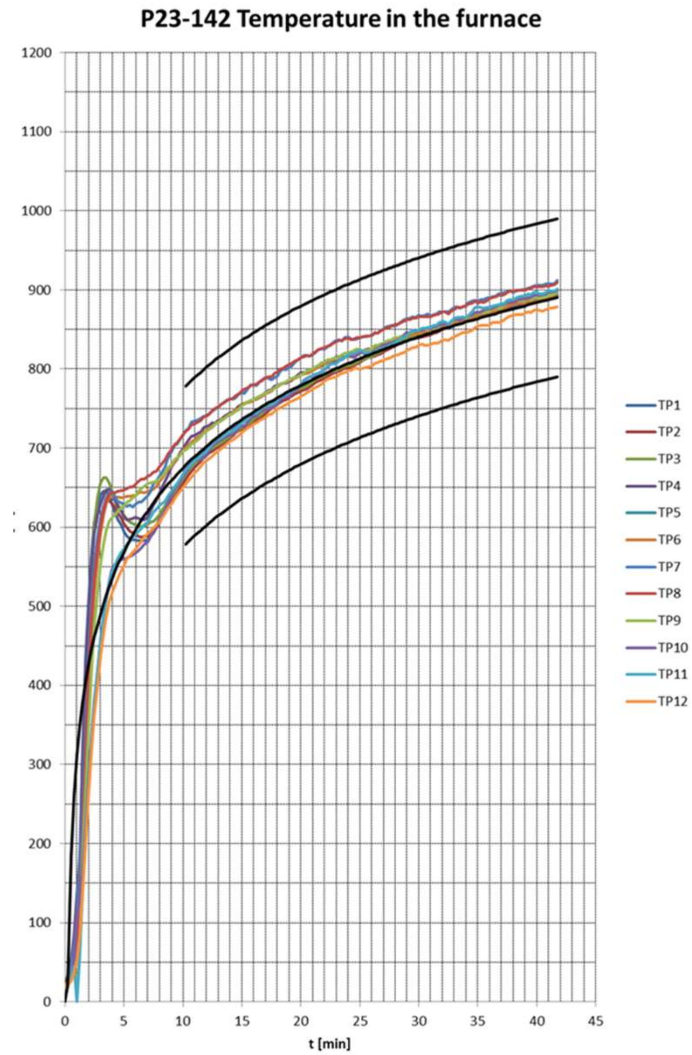


Fire resistance test

Fire resistance test of mechanically loaded samples was performed on 500 x 500 mm samples including one (**loaded in tension**) and second **(loaded in shear**) in two thicknesses: 80 and 160 mm.
Fire resistance test was performed **for 43 minutes**.



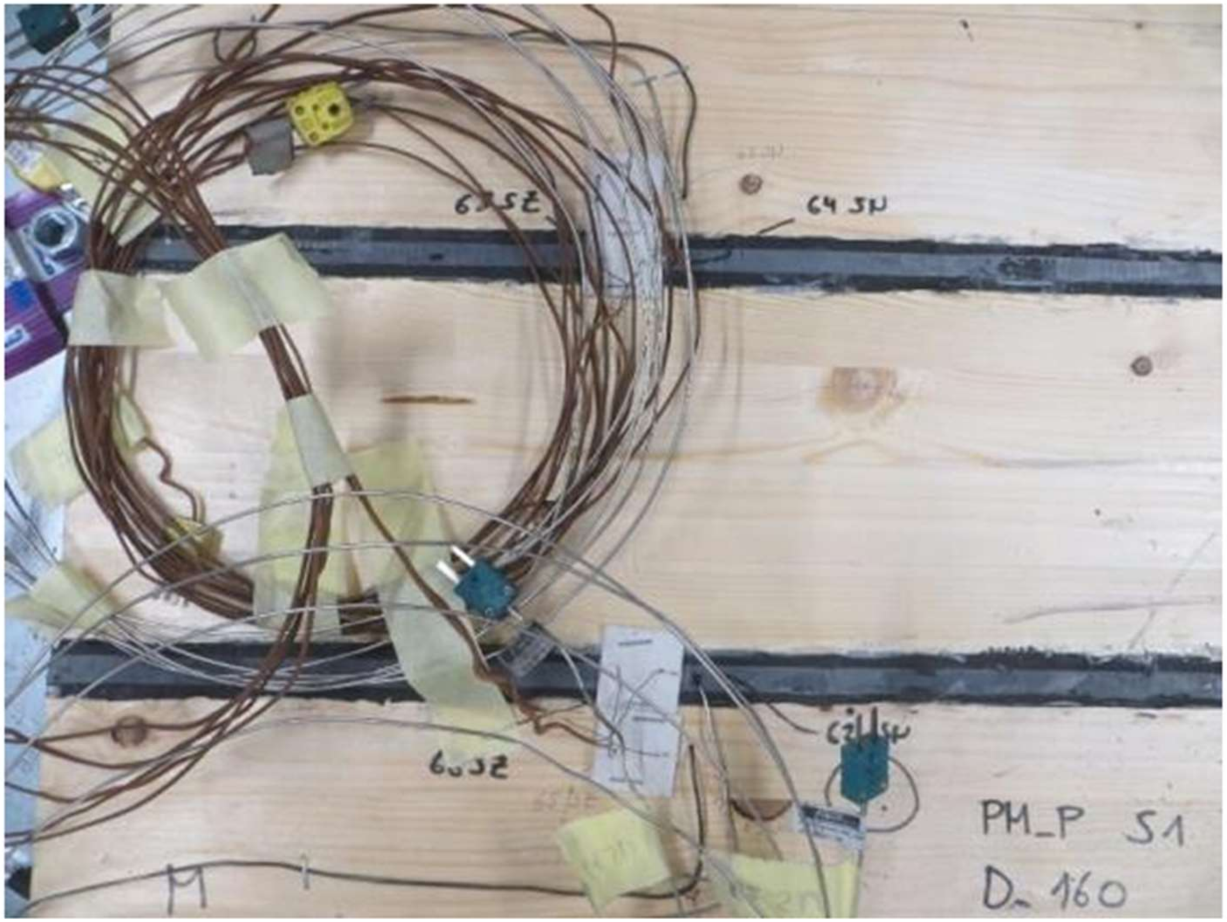
Specimen positioning on the furnace



Shear tests on specimes

Photo A6.45: Hydraulic jack positioning for mechanical shear loading before the fire resistance test
(photo archive, left: 049506d-222, right: 049506d-228)

Thermocouples



Shear test results

Table 2: Applied load.

No.	Name	Loading type	Load [tones]
7	PM_P D_160_S1	Shear	1

Photo A6.55: Specimen 7 after the fire resistance test – unexposed side (left) and exposed side (right)
(photo archive left: 049506d-501 and right:049506d-502)

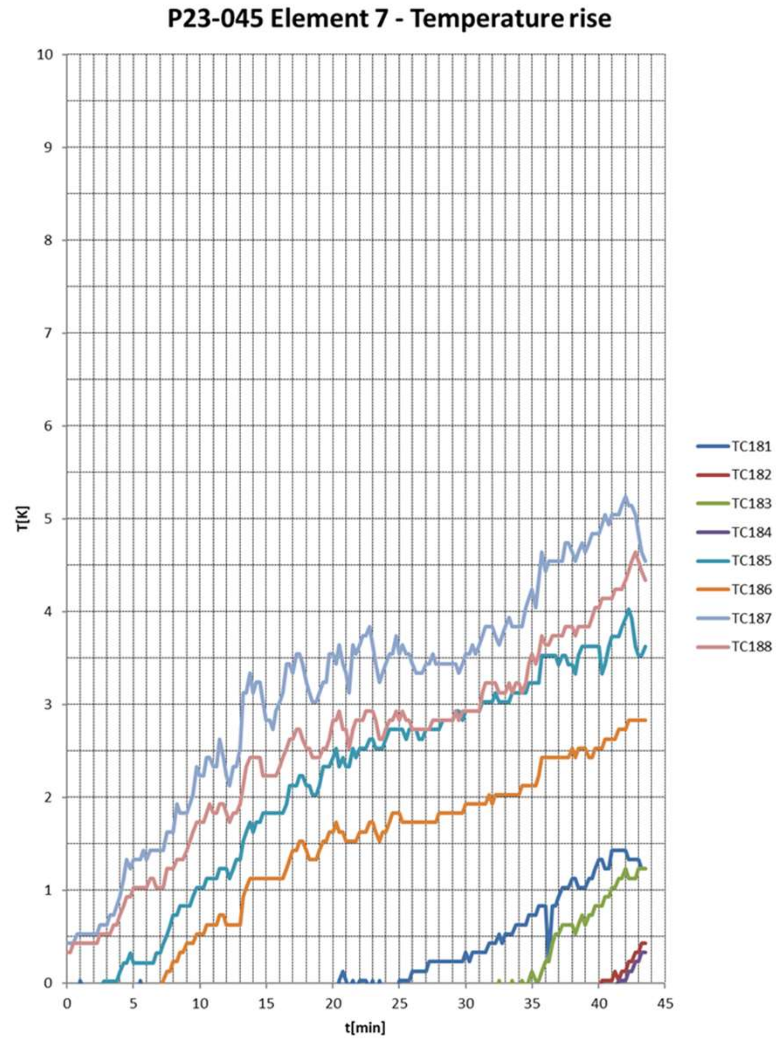


Photo A6.12: specimen no. 12 *(photo archive, left: 049506d-013, middle: 049506d-014, right: 049506d-015)*

Photo A6.22: Mechanical loading of specimen no. 12 in tension *(photo archive 049506d-069)*

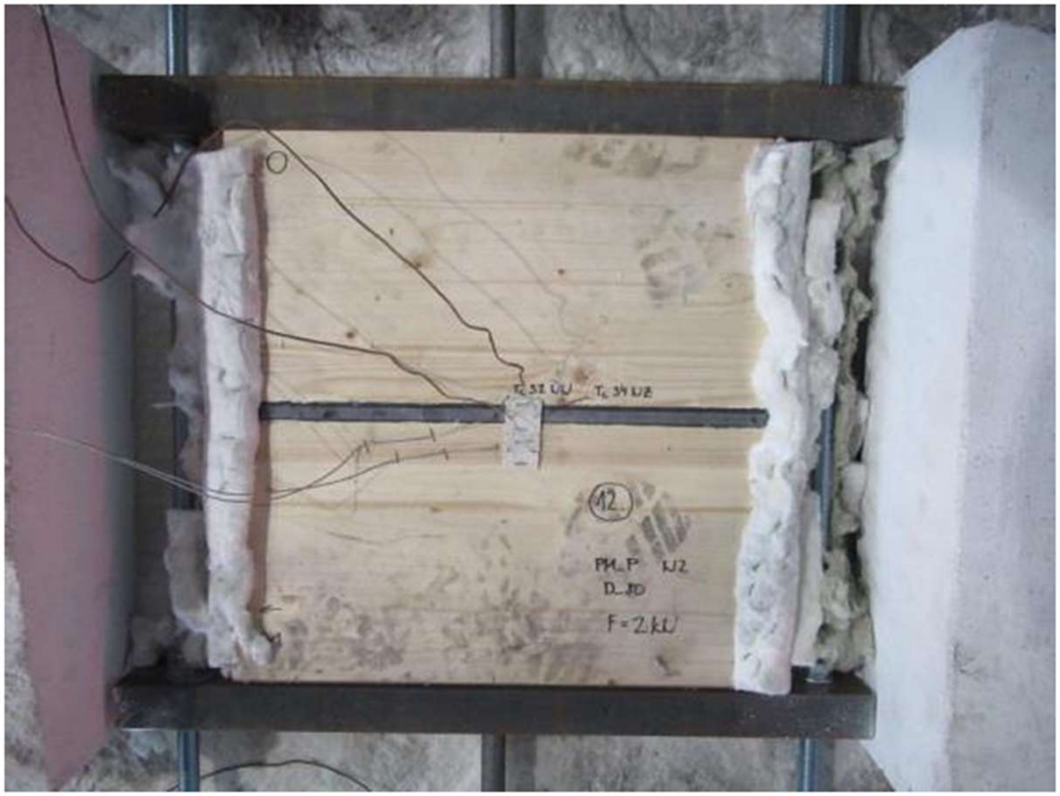
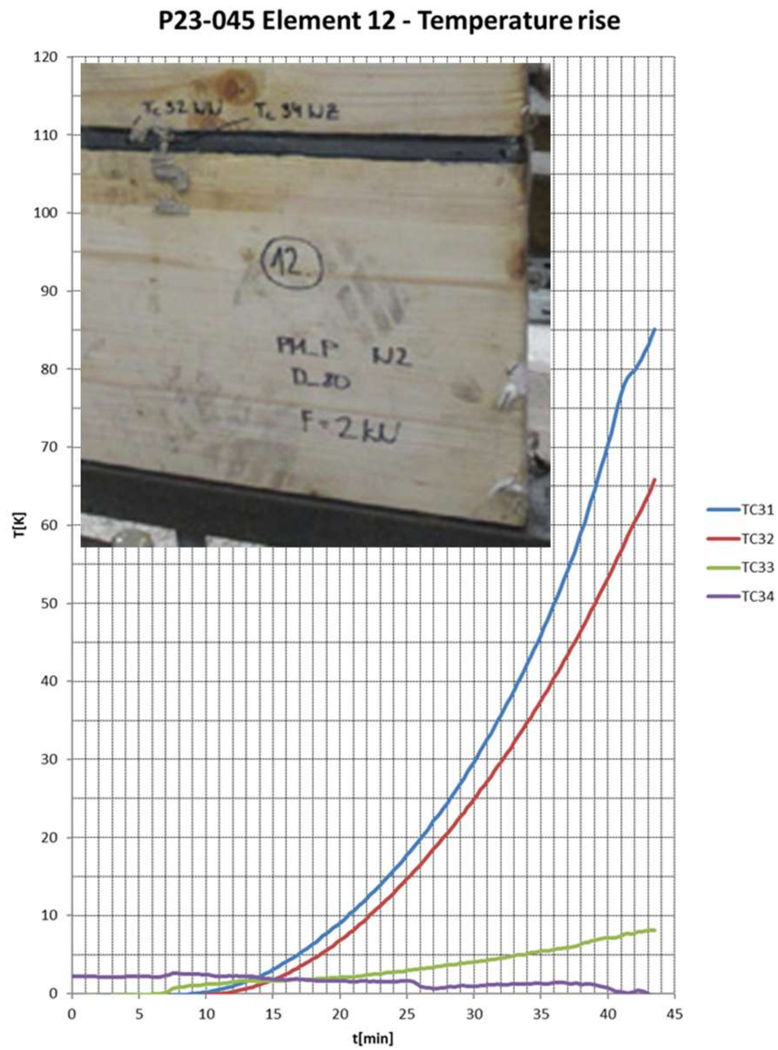


Photo A6.37: Thermocouple placement in specimen no. 12 *(photo archive 049506d-270)*

Table 2: Applied load.

No.	Name	Loading type	Load [tones]
12	PM_P D_80_N2	Tension	0.2

Photo A6.60: Specimen 12 after the fire resistance test – unexposed side (left) and exposed side (right) *(photo archive left: 049506d-447 and right:049506d-448)*

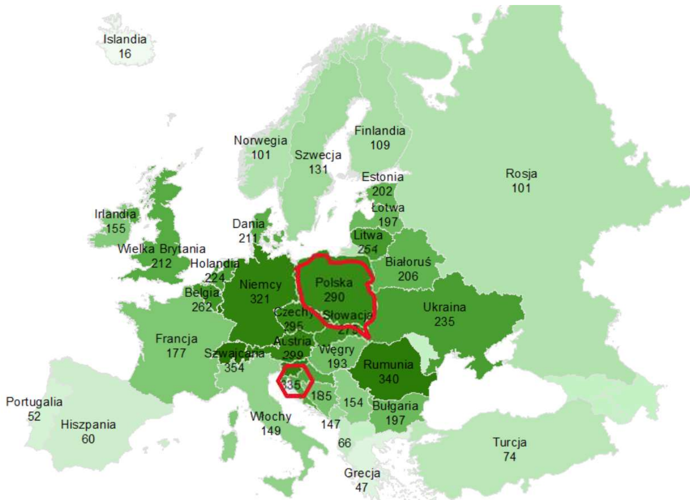


The collapses that occurred were due to exceeded shear strength of the timber and not of the flexible joint. Most of the **flexible joints withstood simultaneous mechanical and fire loading and assured tightness**.

In the fire resistance test it was noticed that timber specimens (with one or two polyurethan joints) **in case of collapse, collapsed through timber**.

The results are of research interest and show that **timber elements of stronger mechanical properties** should be used **to obtain collapse through the flexible joints** in case of fire resistance test.

Project DIAMONDS – international resesarch



NARODOWE CENTRUM NAUKI

OPUS-22 (LAP)

DIAgnostics and Mechanical tests Of aged adhesive layers used in joiNts of wooDen structureS

DIAMONDS

- Slovenian National Building and Civil Engineering Institute
- InnoRenew CoE
- AGH University of Science and Technology
- Cracow University of Technology

ZAG ZAVOD ZA GRADBENIŠTVO SLOVENIJE SLOVENIAN NATIONAL BUILDING AND CIVIL ENGINEERING INSTITUTE

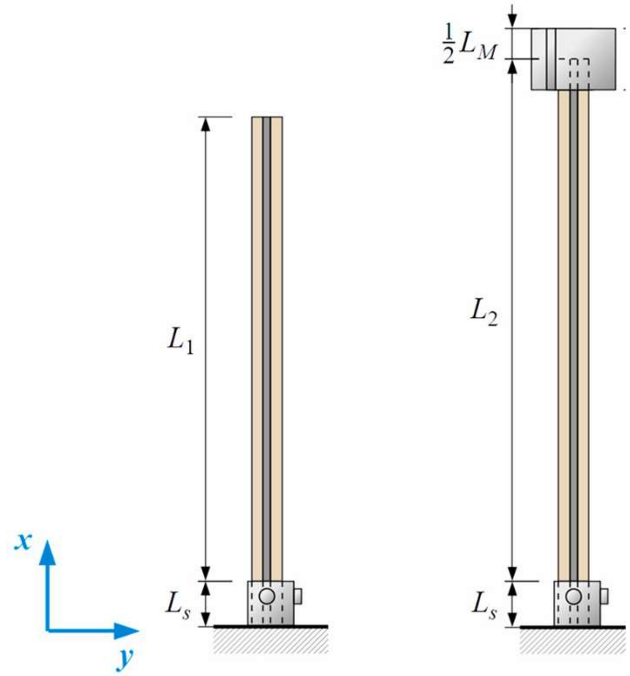
INNORENEW COE

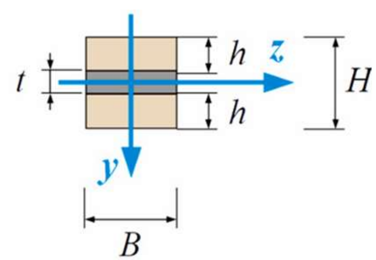
AGH

Cracow University of Technology

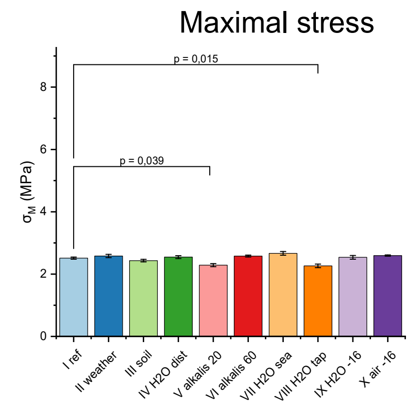
Beech wood based composites
with flexible polyurethane adhesive joints

Shake table excitation





Durability of polyurethanes forming flexible adhesives



Ageing factors examine polyurethane F&R PS (1000 hours of exposition)

Number	Environment type	Factor details	Safe in use
1	Reference	Room conditions, 20 ºC	Yes
2	Atmospheric aging	Atmospheric conditions, 16-31 ºC, up to 5 mm precipitation, unshaded, uncovered	Sensitive to sun radiation
3	Soil	Buried 5 cm deep, atmospheric conditions, 16-31 ºC, up to 5 mm precipitation, unshaded, uncovered	Yes
4	Distilled water	60 ºC	Yes
5	Alkalis	Water solution $Ca(OH)_2$ 2 g/L, 20 ºC	Yes
6	Alkalis – hot	Water solution $Ca(OH)_2$ 2 g/L, 60 ºC	Yes
7	Sea water	20 ºC	Yes
8	Tap water	20 ºC	Yes
9	Frozen tap water	-16 ºC	Yes
10	Cold air	-16 ºC	Yes

Project DIAMONDS – durability tests of beech wood – PU joint

Natural weathering
test site – Poland/Cracow

Natural weathering
test site – Slovenia/Izola

Thank you for your attention!