D4.4 – Outcomes of testing activities

WP4

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1 Executive Summary

The present Deliverable D4.4 "*Outcomes of testing activities"* reports the activities conducted in the Task 4.4 "*Testing and monitoring activities*". The report describes the activities carried out to define the tests to be conducted on the EENSULATE façade module and the results achieved. The activities here reported support the validation of the façade system design (T4.1 "*Design optimization and development of the façade module"* reported in D4.1 "*Detailed design of the EENSULATE envelope system*) and its prototypes (T4.2 "*Manufacturing of the prototype for testing in relevant environment* reported in D4.2 *"Prototypes for testing in relevant environment"*).

The tests reported are:

- Acoustic Mock-Up to be conducted in line with UNI EN ISO 16283-3:2016/EC 1-2016/EC 2-2016 and UNI EN ISO 717-1:2013;
- Performance Mock-Up to be conducted with EN ISO 13830:2005 Curtain Wall Façade;
- Fire Mock-Up to be conducted in medium furnace in Ulster facility.

The results achieved by the tests demonstrate the effectiveness of the EENSULATE facade system design and the validity of the manufacturing process developed in the project.

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Abbreviations and Acronyms

AMU – Acoustic Mock-Up

FMU – Fire Mock-Up

NDT – Non-Destructive Test

PMU – Performance Mock-Up

TGU – Triple Glass Unit

VIG – Vacuum Insulated Glass

1 Introduction

The EENSULATE façade module is an unitized curtain wall façade module which aims at integrating EENSULATE VIG and EENSULATE foam. The design of this façade, as defined in T4.1 “Design optimization and development of the façade module”, is customized based on the technologies to be integrated and the targets expected to be achieved by the EENSULATE project. For this reason, specific tests have been conducted to verify the performances of the façade as well as the effectiveness of the integration of the technologies in a façade system and their potential introduction into the market. With these purposes, tests activities conducted along the EENSULATE project for the single EENSULATE technologies (tests in WP2 for foam poured in façade and tests in WP3 for VIG), find in the EENSULATE façade module test their final validation to demonstrate their applicability in market scenarios as the one of Curtain Wall Facade.

The tests reported in this deliverable resume the activities for test identification, their design, the results, and the conclusions obtained. In particular, the following tests have been conducted:

- Non-Destructive Test (NDT)
- Façade performance tests (air, water tightness, wind load resistance, impact resistance) with the so-called Performance Mock-Up (PMU).
- Acoustic insulation tests with the so-called Acoustic Mock-Up (AMU).
- Fire reaction and behaviour tests with the so-called Fire Mock-Up (FMU).

The next paragraphs present the tests, the preliminary activities for their design, with specifically focus on tests procedures and the achieved results.

2 Objective

The tests of the EENSULATE façade modules were conducted to pursue the following objectives:

- to test prototype and identify weak points and improvement opportunities;
- to design specific test benches for the evaluation of foam density and its distribution in spandrel;
- to demonstrate the correct design for the EENSULATE façade module and its manufacturing, in line with Curtain Wall Façade norm (EN 13830);
- to demonstrate the correct integration of EENSULATE VIG in the façade frame without any “based on standard” tests for façade;
- to demonstrate the behaviour under stress test (impact) of the VIG (e.g., wind load);
- to define the airborne insulation property of EENSULATE façade module;
- to define the fire behaviour of EENSULATE façade module;
- to define the fire behaviour of VIG in comparison with TGU baseline.

The overall results represent the achievements of the EENSULATE façade module and define the potential and limits for its application in the Curtain Wall Façade market.

3 Methodology

The tests illustrated in the present report are the results of the research activities conducted throughout the overall the project. Indeed, the tests definition was defined on the basis of the following methodology:

- **EENSULATE façade requirements** – based on the output of T4.1 "*Design optimization and development of the façade module*", specific tests need to be designed to comply façade requirements for its applicability on the market. Ats this purpose the main aspects to be considered are:

- *Façade market requirements* – the façade market for prefabricated building envelope is a well mature sector where specific norms and standards are defined. The main references are the requirements defined by EN 13830 European Standard which "*specifies requirements of curtain walling kit intended to be used as a building envelope to provide weather resistance, safety in use and energy economy and heat retention and provides test/assessments/calculation methods and compliance criteria of the related performances. The curtain walling kit covered by this standard should fulfil its own integrity and mechanical stability but does not contribute to the load bearing or stability of the main building structure*" [1]. This is the reference norm to have CE certification.

- *EENSULATE façade project requirements* – specific project requirements are part of the design in early phase and tests in late phase and also EENSULATE façade need to comply with project specifications. In particular, this is referred to project expected results in term of acoustic (52 dB) as well as investigation needed to understand the behavior of spandrel foaming and fire resistance.

- **Testing activities** – based on the EENSULATE façade requirements the tests activities are set up:

    - *Tests definition* – the tests are selected to comply with requirements for façade and EENSULATE expected outcomes.

    - *Preparation phase* – the norms and therefore the method statements, and the facilities for each test are defined.

    - *Design and manufacturing* – the EENSULATE façade modules are designed for each test and manufactured.

    - *Test and performances achieved* – the tests are conducted, the results collected.

- **Analysis of results** – based on results achieved, an analysis is conducted to validate the EENSULATE façade module on the base of its requirements and to identify weak points and improvement opportunity for further activities.

The above-mentioned methodology is developed in the following sections for the tests conducted.

4 Mock-up: test preparation, façade design, test, performances, and results

4.1 Performance Mock-Up

From a technological point of view, the EENSULATE facade is a unitized system, and its performances must be validated in line with EN ISO 13830 for Curtain Wall Façade.
The test, for this specific technological product, needs to provide an analysis of norms and to understand how this façade allows the buildings to achieve higher performances.

4.1.1 PMU test preparation phase

The test has been conducted by an accredited testing facility authorized to issue official test report to obtain CE certification for EN 13830. The method statement of the tests has been specified and the sequence of the test is so defined:

- **Façade performance test** – During the performance test the parameters reported in Table 1 have been tested. The table also shows the pressure to be used in the test and the required criteria for passing the test according to the UNI EN references 13830:2005.

Table 1 – Test sequence in accordance with EN 13830:2005

TEST	TEST PRESSURE	PASS/FAILURE CRITERIA	UNI EN REFERENCES
Air permeability -Leed certification	± 75 Pa	Air permeability ≤ 0.3 l/sm^2 ≤ 1.08 m^3/hm^2	NFRC 400, ASHRAE 90.1 (5.4.3.2)
Air permeability Infiltration /Exfiltration	±600 Pa	Air infiltration rate ≤ 1.5 m^3/hm^2 at +600 Pa	UNI EN 12152, UNI EN 12153
Static water penetration resistance	±600 Pa	No leakage	EN 12154, UNI EN 12155
Wind resistance serviceability	±1350 Pa	Mullion deflection limit: 3600/300 + 5 = 17.0 mm Residual deformation: 0.05xmax measured deformation or 1 mm (see table 5 for detection points)	EN 13116
Air permeability Infiltration /Exfiltration	±600 Pa	Air leakage shall not exceed that measure at point 1 by more than 0.3 m^3/hm at peak pressure	UNI EN 12152, UNI EN 12153
Static water penetration resistance	±600 Pa	No leakage	UNI EN 12152, UNI EN 12153
Wind resistance safety	1.5 wind design pressure ±2025 Pa (1.15x1350)	Integrity Mullion Residual deformation = 7.2 mm (3600mm/500)	UNI EN 12179

- **Impact test** - Test sequence EN 14019:2016 (CE) Double tyres in accordance with UNI EN 12600 was conducted. Impact test both from inner side and outer side are performed as represented in the Figure 5. In the following table are listed the impact tests conducted.

Tab. 2 - IMPACT TEST - Test sequence EN 14019:2016 (CE) Double tyres in accordance with UNI EN 12600				
	POSITION	IMPACTOR	EXTERNAL Cat. E INTERNAL Cat. A	TST PASS REQUIREMENTS - EN 14019
1	CENTER OF THE MULLION, VERTICAL BETWEEN THE CONNECTION (EXTERNAL ONLY)	DOUBLE TYRES UNI EN 12600	Class E4 (343 J, 700 mm)	- No fragments with a mass greater than 50 g must fall; - No crack or opening through which test block E2 conforming to EN 1630 (ellipse) can be introduced; - Permanent deformations of the frame elements, including connections and fixings, are allowed, as long as there are no cracks or breakages separating the frame elements, connections and fixings; - The specimen must not detach or displace; - Each unit must not detach or displace.
2	CENTER OF THE TRANSOM (INTERNAL, EXTERNAL)	DOUBLE TYRES UNI EN 12600	Class E4 (343 J, 700 mm) Class I5 (466 J, 950 mm)	
3	END OF THE TRANSOM, AT A DISTANCE OF 150 mm FROM THE CONNECTION WITH THE MULLION (EXTERNAL ONLY)	DOUBLE TYRES UNI EN 12600	Class E4 (343 J, 700 mm)	
4	END OF THE MULLION, AT A DISTANCE OF 150 mm FROM THE END ITSELF (EXTERNAL ONLY)	DOUBLE TYRES UNI EN 12600	Class E4 (343 J, 700 mm)	
5	CENTER OF UNIT (INTERNAL, EXTERNAL)	DOUBLE TYRES UNI EN 12600	Class E4 (343 J, 700 mm) Class I5 (466 J, 950 mm)	

Figure 1 – Impact test predicted in accordance with UNI EN 12600

As reported in Figure 2 and Figure 3, 18 tests have been carried out, spread in different strategic locations of the unit (12 from the external and 6 from the internal). In the following pages are shown pictures regarding the main test's locations.

Impact area	Condition	Class	Drop height [mm]	Effect
1	safety	I5	950	no damage
2	safety	I4	700	no damage
3	safety	I5	950	no damage
4	safety	I5	950	distortion of the panel
5	safety	I5	950	no damage
6	safety	I4	700	no damage

Figure 2 -Internal impact resistance

Impact area	Condition	Class	Drop height [mm]	Effect
1	safety	E5	950	safe breakage of the glass
2	safety	E5	950	no damage
3	safety	E5	950	no damage
4	safety	E5	950	no damage
5	safety	E5	950	no damage
6	safety	E5	950	no damage
7	safety	E5	950	no damage
8	safety	E5	950	no damage
9	safety	E5	950	no damage
10	safety	E5	950	no damage
11	safety	E5	950	no damage
12	safety	E5	950	no damage

Figure 3 - External impact resistance

- **Gauge deflection verification** – based on façade mechanical simulation, the correspondence between the value from simulation and the one from test is compared to confirm the theoretical component. Some sensors were placed towards the mullions and transom to investigate their deflection during the performance test. In the following table are listed the locations of the gauges.

Table 3 - DEFLECTION GAUGE LOCATION	
A	Unit Mullion - Top fixing bracket
B	Unit Mullion - Centre between fixings
C	Unit Mullion - Centre of DGU Panel
D	Unit Mullion - Bottom fixing
E	Bottom Transom - Left
F	Bottom Transom - Centre
G	Bottom Transom - Right

Figure 4 – Deflection gauge location

The success of all these tests allows it to accomplish EN ISO 13830:2005 standards, enabling the EENSULATE façade to obtain the CE certification. The following picture shows the technical drawing of the PMU with the position where to conduct the impact and deflection gauge test.

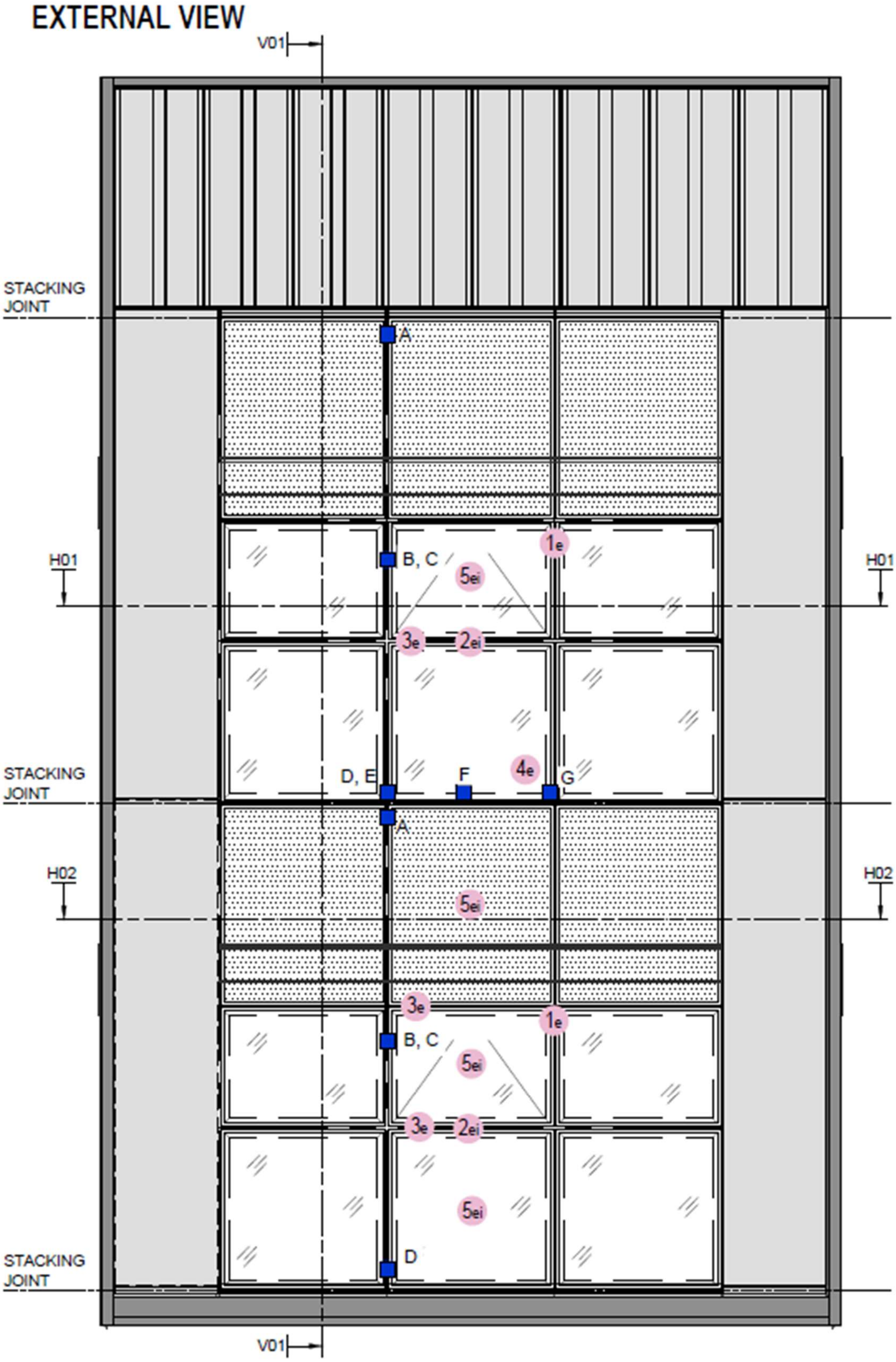


Figure 5 - EENSULATE PMU elevation drawing. The drawings report the impact tests onto the façade.

4.1.2 PMU design

The test sample is a section of the EENSULATE façade curtain walling composed of 6 façade modules, arranged on two-storeys:

- The bottom story consists of the following 3 Units:
  - Two EENSULATE façade modules with VIG, modular dimension 1139,5 x 3600 mm, split into an upper spandrel panel of 1139,5 x 1500 mm and a central vision area of 1139,5 x 900 mm, and a bottom vision area of 1139,5 x 1200 mm;
  - One openable EENSULATE façade module with VIG, modular dimension 1139,5 x 3600 mm, split into an upper spandrel panel of 1139,5 x 1500 mm and a central openable area of 1139,5 x 900 mm, and a bottom vision area of 1139,5 x 1200 mm;
- The top story consists of the following 3 Units*:*
  - Two EENSULATE façade modules with VIG, modular dimension 1139,5 x 3600 mm, split into an upper spandrel panel of 1139,5 x 1500 mm and a central vision area of 1139,5 x 900 mm, and a bottom vision area of 1139,5 x 1200 mm;
  - One openable EENSULATE façade module with TGU, modular dimension 1139,5 x 3600 mm, split into an upper spandrel panel of 1139,5 x 1500 mm and a central openable area of 1139,5 x 900 mm, and a bottom vision area of 1139,5 x 1200 mm;

The EENSULATE façade modules are made of laminated VIG, except for the central upper unit, which is equipped with TGU. In this way it is possible to test and compare the market benchmark for glass in façade (TGU) with the EENSULATE VIG and comparing the effectiveness of VIG to comply with market baseline.

Two different glass typologies are included in EENSULATE façade modules:

- VIG glass for vision area, nominal thickness 19,77 mm
- TGU glass for the vision area, nominal thickness 47,52 mm

The whole glass perimeter is enclosed by a vulcanized compatible EPDM frame and fitted from the outside resting against compatible EPDM setting blocks, which also act as backing material for the structural sealant. The modules were installed in sequence, inserting special EPDM gaskets to provide vertical and horizontal tightness and suitable weep holes. The specimen was installed on a metal framework made of steel load-bearing structure covered with 2 mm sheet steel, in such a way as to create the airtight chamber needed for the test.

As usual in EN ISO 13830:2005 tests, the units have been positioned in two floors to be able to test all the junctions between units, both horizontal as well as vertical cones.

The item, conditioned for the previous 4h at the conditions required by the normative references, it was mounted on the test rig and it was submitted, in sequence, to the tests.

4.1.3 PMU test and performances achieved

In line with the test as designed, the PMU has been done in an accredited test chamber and the activities conducted by an independent third party. Figure 6 shows the PMU installed and ready for the test. The other following figures show the PMU during different test sequences.

Figure 6 - PMU protype installed and ready for the test

Figure 7 – Impact on the openable windows transom

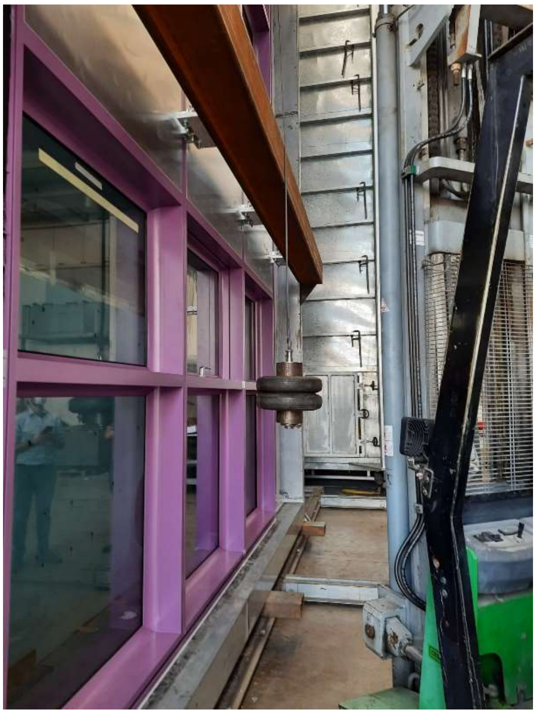


Figure 8 - Impact on the openable windows transom

Figure 9 – Impact on the spandrel part top level in the metal sheet

Figure 10 – Impact on the spandrel part top level in the metal sheet

Figure 11 - Impact on the openable vent

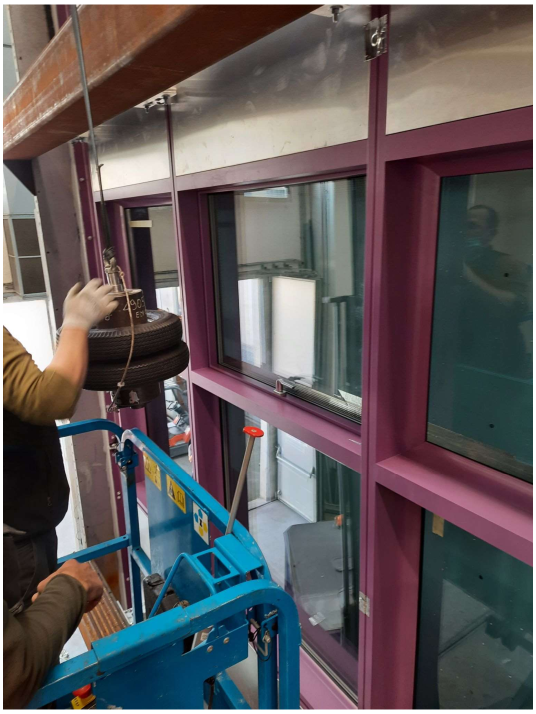


Figure 12 - Impact on the openable vent

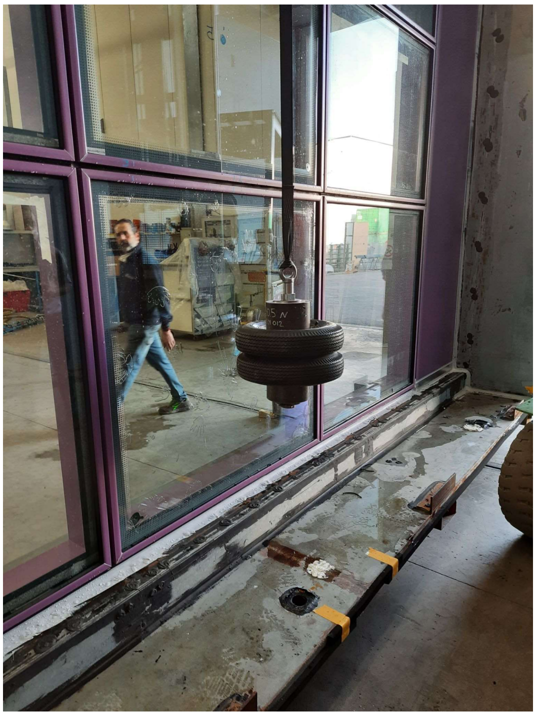


Figure 13 - Impact on the vision unit with VIG

Figure 14 - Impact on the vision unit with VIG

4.1.4 PMU results

The following picture shows the results from the performance mock-up. In the last column the classifying results are listed for each parameters tested.

Activity		Test reference	Classification reference	Class*
air permeability through fixed parts	related to overall area	UNI EN 12153	UNI EN 12152	**A4**
	relating to fixed joint length			**A4**
air permeability through openable parts	positive pressure	UNI EN 1026	UNI EN 12207	**4**
	negative pressure			**4**
watertightness		UNI EN 12155	UNI EN 12154	**R7**
resistance to windload under design load 1350 Pa and -1350 Pa		UNI EN 12179	UNI EN 13116	**pass**
internal impact resistance		UNI EN 14019	UNI EN 14019	**I4**
external impact resistance		UNI EN 14019	UNI EN 14019	**I5**

Figure 15 – Performance test result

The results allow the compliance of EENSULATE façade module with the EN13830 and therefore its full applicability for European market as curtain wall façade solution. The comparison between TGU and VIG demonstrate the effectiveness of EENSULATE façade in relation to the market benchmark and innovation by VIG introduced with EENSULATE.

4.2 Acoustic Mock-Up

The Acoustic Mock-Up (AMU) test has the purpose to identify the insulation property of the EENSULATE façade under different noise frequencies from a sound surgent positioned outside the test chamber towards the inner part of the chamber.

4.2.1 AMU test preparation phase

The test conducted for façade acoustic testing is:

- **Acoustic airborne insulation (IN-OUT test)** –for Curtain Wall Façade (unites façade with mineral wool and Double Glazed Unit), the usual target is usually 42 dB, but the expected target for EENSULATE façade defined proposal stage is 52 dB. The reference norm is UNI EN ISO 16283-3:2016/EC, 1-2016/EC, 2-2016 and UNI EN ISO 717-1:2013 (IN-OUT test).

4.2.2 AMU design

AMU is designed to be conducted in Focchi acoustic test chamber, the same chamber used for acoustic test for foam composition during WP2 activities. This chamber is inside Focchi premises and it is commonly used for acoustic tests conducted in projects, but the test is carried out and reported by a third accredited entity authorised to issue the results report.

The test sample is a section of curtain walling composed of 9 Units, arranged on two-storeys:

- The bottom story consists of the following 6 EENSULATE façade modules:
    - Lower part with 3 spandrel façade modules, modular dimension 1139,5 x 1500mm. More specifically, the Spandrel Units are composed by:
        - Frame, mullions and transoms made from bespoke aluminium-alloy extrusions butted together and secured using self-tapping screws and silicone in the joints;
        - Alu sheet, secured with self-drilling screws and sealed around the edges to the unit aluminium frame;
        - Plasterboard;
        - Polyurethane foam of suitable thickness;
        - Laminated glass nominal thickness,
    - The upper part with 3 EENSULATE façade module, modular dimension 1139,5 x 3600 mm, split into an upper spandrel panel of 1139,5 x 1500 mm and a central vision area of 1139,5 x 900 mm, and a bottom vision area of 1139,5 x 1200 mm. A spandrel panel formed from the inside by:

- Frame, mullions and transoms made from bespoke aluminium-alloy extrusions butted together and secured using self-tapping screws and silicone in the joints
- Alu sheet secured with self-drilling screws and sealed around the edges to the unit aluminium frame;
- Plasterboard;
- Polyurethane foam of suitable thickness.
- VIG with laminated glass.

The vision panel formed from the inside by:

- Frame, mullions and transoms made from bespoke aluminum-alloy extrusions butted together and secured using self-tapping screws and silicone in the joints;

- A VIG glass for the vision area is formed (starting from inside) by:
    - Mid-iron toughened glass;
    - Vacum cavity;
    - Mid-iron toughened glass;
    - PVB;
    - Mid-iron HS;

- The upper storey consists of the following 3 vision façade modules, modular dimension 1139,5 x 1200 mm. More specifically, the Spandrel Units are composed by:
    - Frame, mullions, and transoms made from bespoke aluminium-alloy extrusions butted together and secured using self-tapping screws and silicone in the joints.
    - Alu sheet secured with self-drilling screws and sealed around the edges to the unit aluminium frame.
    - Plasterboard.
    - Polyurethane foam of suitable thickness.
    - Laminated glass.

The glass perimeter is enclosed by a vulcanized compatible EPDM frame and fitted from the outside resting against compatible EPDM setting blocks, which also act as backing material for the structural sealant. The modules were installed in sequence, inserting special EPDM gaskets to provide vertical and horizontal tightness and suitable weep holes.
The following table reports the general dimension of the acoustic mock-up:

Nominal length of the item, from the outside	3700,5 mm
Nominal height of the item, from the outside	6372 mm
Measured length of the item, from the receiving room side	2427 mm
Measured height of the item, from the receiving room side	3724 mm
Effective acoustic surface (2427 mm × 3724 mm)	9,04 m²

Figure 16: dimension of the Acoustic Mock-Up.

The technical drawing regarding the design of the Acoustic mock-up is reported below:

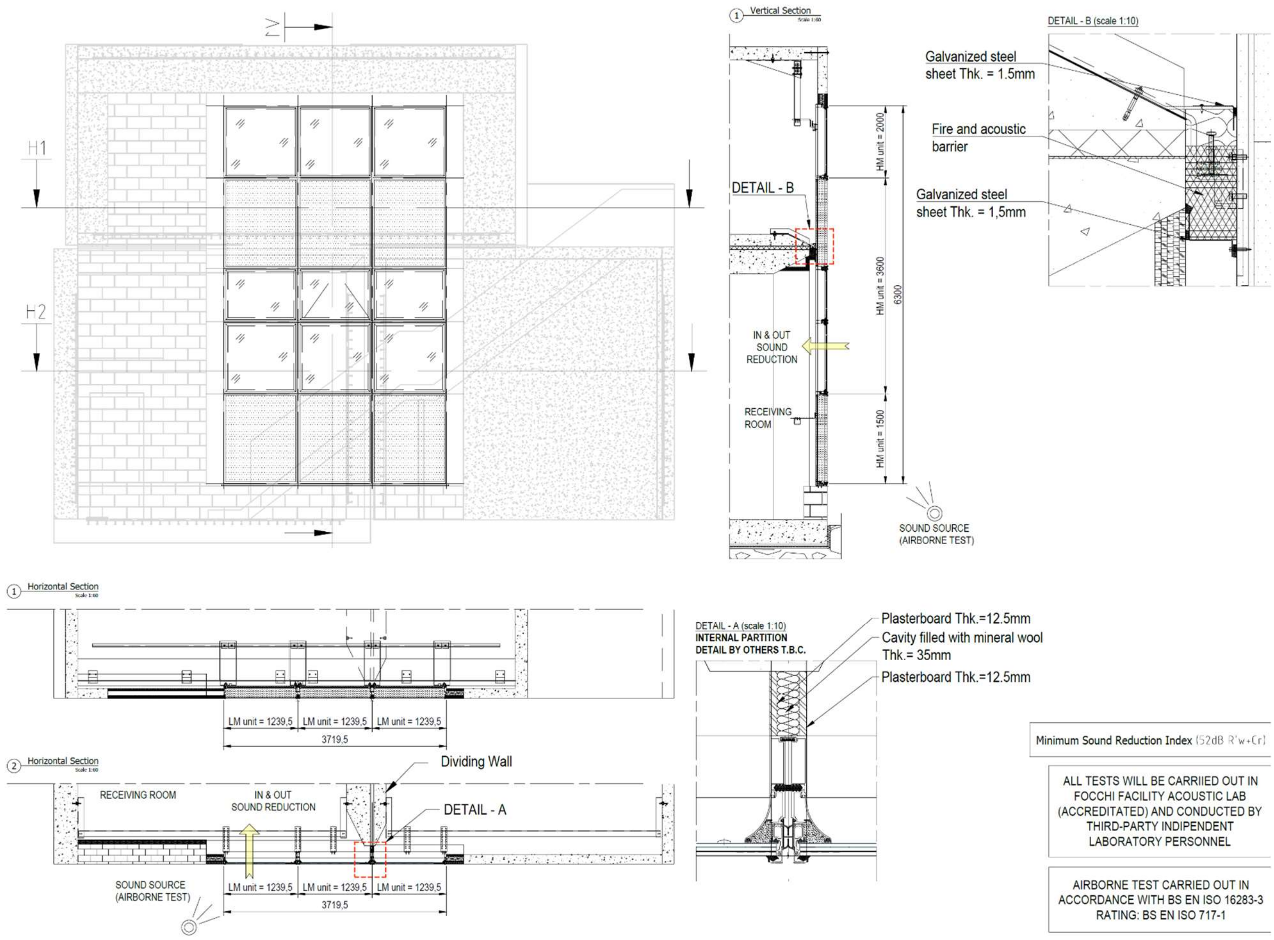


Figure 17 - Acoustic mock-up technical drawing

4.2.3 AMU test and performances achieved

The acoustic test was conducted by placing a sound source on the ground at the distance, from the centre of the item, of at least 7 m with an incidence angle of 45° ± 5°. Turning on the sound source, emitting white noise, the sound pressure levels were measured, at the same time, on the external surface of the item and in the receiving room in n° 10 fixed microphone positions randomly distributed; the averaging time was 30 s. Turned off the sound source, in the receiving room the background noise was measured after the reverberation time, using the interrupted noise method.

Figure 18 - Acoustic mock-up during the installation

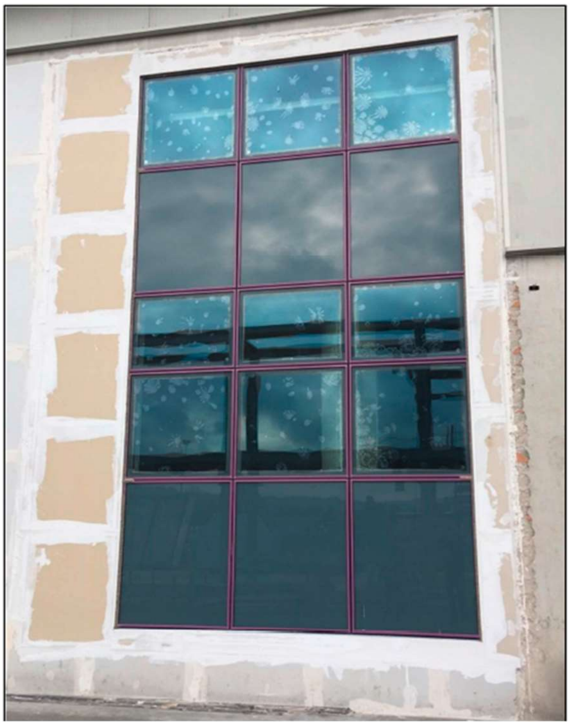


Figure 19 - Acoustic mock-up before the testing activities

Figure 20 - Acoustic chamber

Figure 21 - Acoustic chamber façade detail

Figure 22 - Acoustic test - during the testing activities

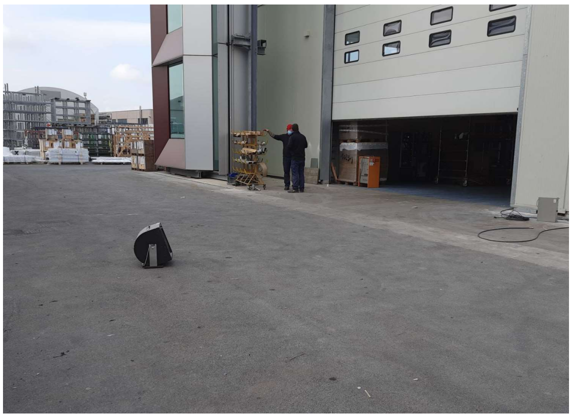


Figure 23 - Acoustic test the sound source positioning

4.2.4 AMU results

The acoustic result has been calculated and certificated by a third entity.

The results are reported below:

Item effective measuring surface:
9,04 m²

Distance loudspeaker - centre of the item:
7,79 m

Incidence angle:
45,1°

Receiving room volume:
89,8 m³

Single-number rating and adaptation terms:

$$R'_{45°w}\ (C, C_{tr}) = 42\ (-1, -4)\ dB^*$$

(*) single-number quantity of the apparent sound reduction index measured in steps of 0,1 dB and uncertainty of measurement of the single number quantity $U(R'_{45°,w})$:

$R'_{45°,w} = (42{,}4 \pm 1{,}5)$ dB

$R'_{45°,w} + C = (40{,}9 \pm 1{,}6)$ dB

$R'_{45°,w} + C_{tr} = (38{,}4 \pm 1{,}7)$ dB

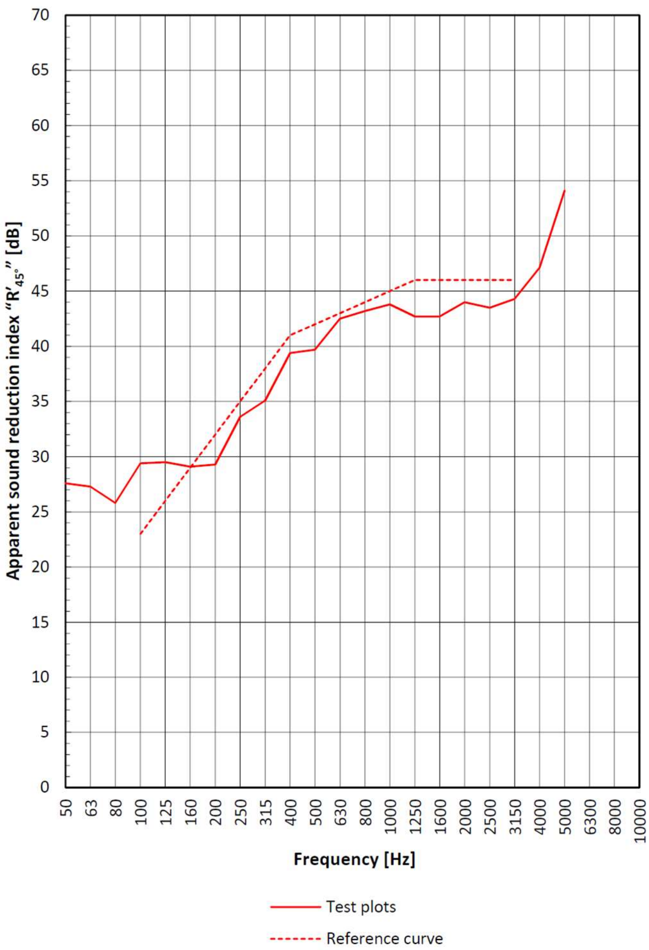


Figure 24: Acoustic Mock-Up test results.

The EENSULATE façade has achieved 42dB of insulation. The result can be considered effective for the façade market (like the façade with DGU plus acoustic PVB), but lower than planned. The reasons are:

- Incorrect target definition. During this target definition, the 52 dB was considered achievable since the know-how on VIG was lack. The EENSULATE facade achieves this target.

- Incorrect lamination of VIG. Due to manufacturing error in VIG production, the lamination was not correct with consequent melting of PVB. This could have caused some loss in the overall performance.

To understand the possible incidence of incorrect lamination on VIG for the overall acoustic performance, a specific test has been conducted only on VIG.

4.2.5 Additional acoustic test on VIG

The test has been conducted on two VIGs:

- 1200 mm x 1160 VIG with correct lamination.

- 1200 mm x 1160 VIG with incorrect lamination (same VIG used during AMU);

The results demonstrate that the VIG with correct lamination achieves 40.8 dB, while the incorrect laminated VIG 40 dB. The results demonstrate small differences which are not relevant for the overall performances of the AMU, therefore the 42 dB for EENSULATE façade can be considered the right reference.

4.3 Fire Mock-Up

The fire mock-up tests were conducted on samples of EENSULATE façade modules with VIG and TGU to have a comparison of EENSULATE façade module with market benchmark glass (TGU) at the FireSERT laboratory at Ulster University. The thermal behaviour of the newly developed VIG facades was benchmarked against that of the traditional TGU facades in the fire tests. Four tests were conducted, and further details are presented in the following sections.

4.3.1 FMU test preparation phase

For the fire test, the following units have been used:

- n° 3 tests of EENSULATE module (VIG and Foam)
- n°3 tests of EENSULATE benchmark (TGU and Mineral Wool)

Slow rate temperature increases instead of the standard testing curve were used. In fact, the glass is going to fail/brake/crack before 200 ºC so there is no point to increase the temperature according to the standard temperature curve. Instead, it was decided to gradually increase temperature until cracking occurs. Therefore, it was not applied the EN13501 collapsing of façade standard (structural silicone temperature service 150°, aluminium melting 600°). For this reason, the façade has not been tested in a large furnace but in a medium scale one, thus enabling to perform more science-oriented measurements.

Figure 25 – Medium furnace

A medium sized furnace with an internal compartment measuring 1.5 x 1.5 x 1.5 m^3 was utilised for all the tests. The furnace has a top cover and three vertical side walls lined with insulating firebricks to ensure effective heat containment, preventing heat losses which could compromise the accuracy of the test results. Heating was achieved by means of five gas burners located within the walls of the furnace (Figure 26). Each specimen was sandwiched between two vertical plasterboard walls built into the front frame of the furnace as shown in Figure 27.

Thermocouple's custom made from fibreglass insulated flat twin cable wires and copper discs were installed on each specimen at two locations on the fire exposed side and fourteen locations on the unexposed side of the specimens to accurately capture the temperature variations across each module during the test. The copper discs were soldered onto one end of the thermocouple and firmly secured to the glass surface with fibre pads and fire cement (Figure 28), while the second end of the thermocouple terminated into a pin plug which was connected to a data logger to enable a smooth transmission of temperature readings during the test. Details of the locations of the thermocouples and their designations are provided in Figure 29 and Figure 30. The specimens were lifted and positioned on the furnace as depicted in Figure 31 following the installation of the thermocouples at the designated locations.

A radiometer was installed at 0.5m from the unexposed surface of the specimen to monitor the heat flux variation in the specimens during the tests. The data logger was connected to a laptop equipped with software which recorded in real-time temperature readings from the thermocouple during the test.

Figure 26 - Furnace interior

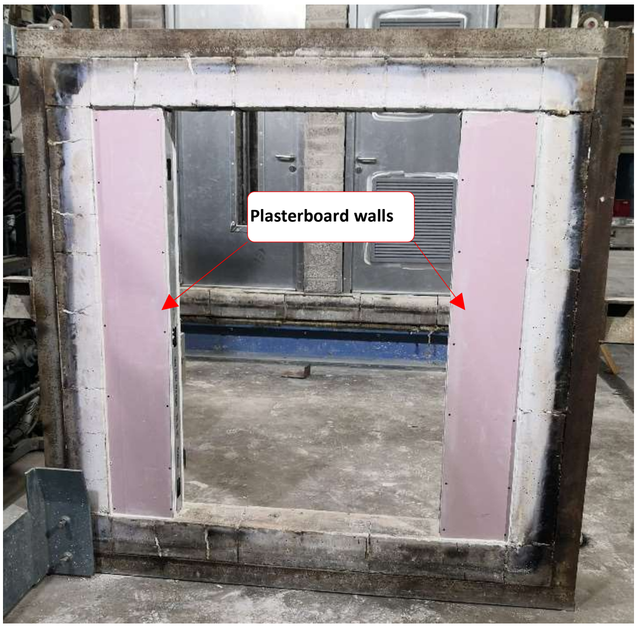


Figure 27 - Plasterboard wall installation

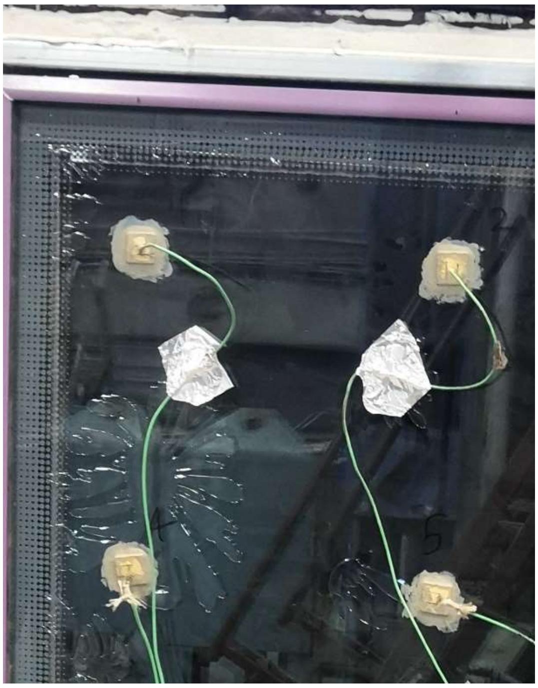


Figure 28 - Thermocouple installation

Fig. 4.3.1

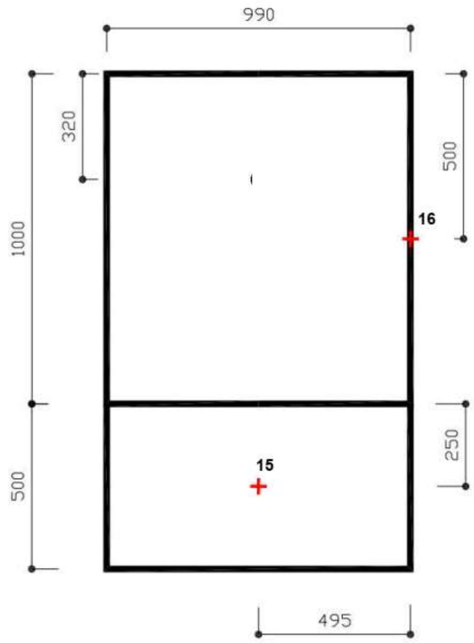


Figure 29 - Thermocouple locations exposed side

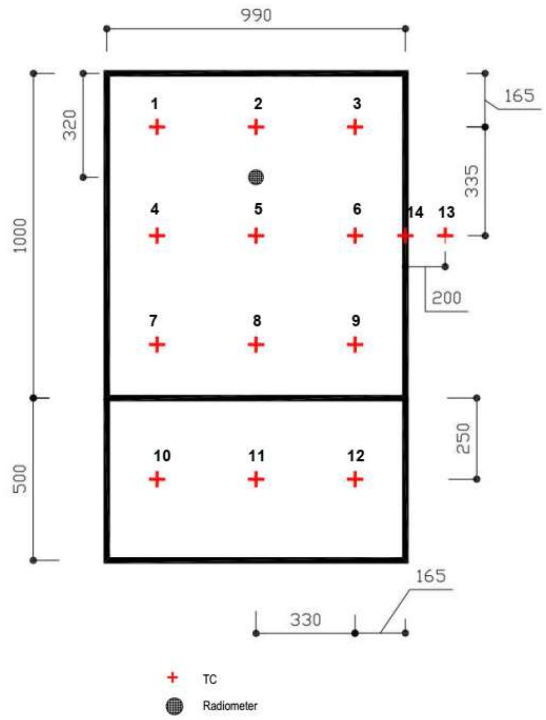


Figure 30 - Thermocouple & radiometer locations unexposed side

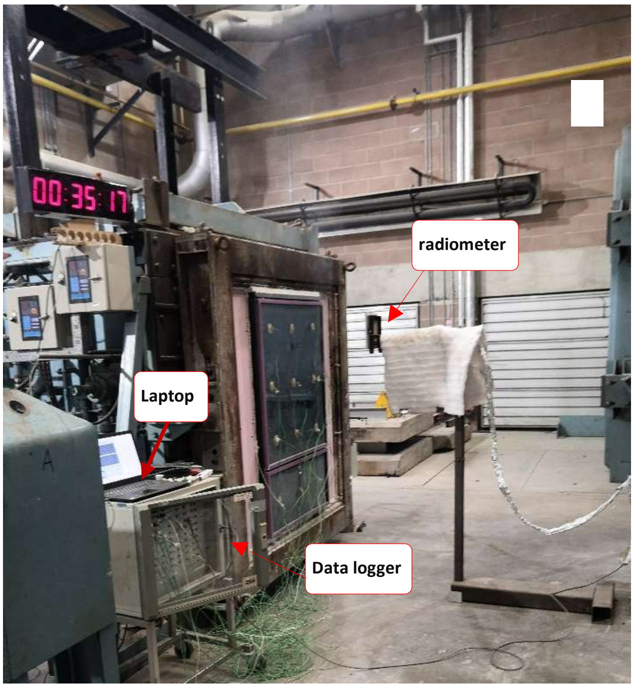


Figure 31 - Full specimen set-up

4.3.2 FMU design

The fire tests were conducted in two batches with each batch consisting of two tests i.e. one VIG and one TGU module. It was deemed necessary to modify the ISO 834 fire curve for the tests since the use of the curve in its original form could potentially result in an abrupt failure of the glass panel due to the fast rise in temperature in the initial segments of the curve. 35% and 50% of the standard ISO 834 fire curve were adopted for the first and second batch tests, respectively (Figure 32). These modifications allowed the specimens to be heated at a relatively slower pace thereby preventing premature cracking and outright failure. One set up procedure was followed for the specimens tested, with little adjustments in each test as required. A generic description of the test set-up procedures for the specimens is provided here. For each test, the furnace front frame was lifted and mounted on the furnace, following the installation of the specimen in between the plasterboard walls. Preliminary checks were performed on the thermocouple connections, laptop and dataloggers to ensure that everything was intact. It was ensured that readings from the thermocouples were correctly displayed on the laptop display. At the completion of each test, the integrity of the custom-built plasterboard walls was checked to see if any repairs or modifications were necessary before the next test. Each specimen was exposed to the thermal load for 60 minutes.

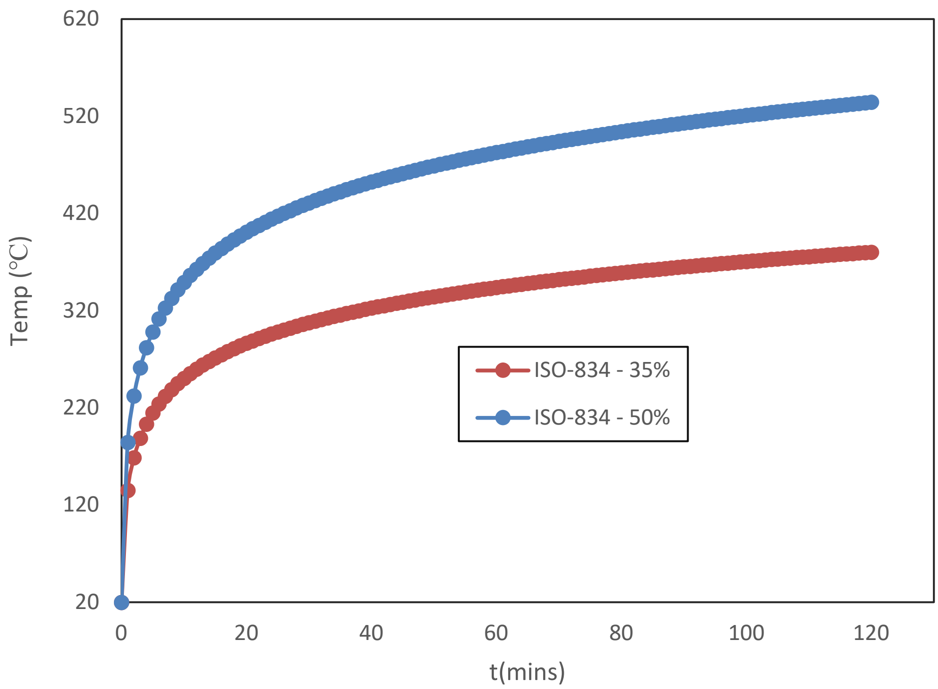


Figure 32 - Modified ISO 834 fire curves

4.3.3 FMU test and performances achieved

The fire performance of the specimens observed in the tests is discussed in this section. The temperature versus time plots from the installed thermocouples (TC) are presented to provide an insight into the temperature distribution and heat transfer for each specimen during the test. The furnace was programmed to closely follow the design fire curves, i.e. 35% & 50% of the ISO 834 curve. The furnace and design fire temperature versus time plots for both batches presented in Figure 33 and Figure 34 show very reasonable agreement.

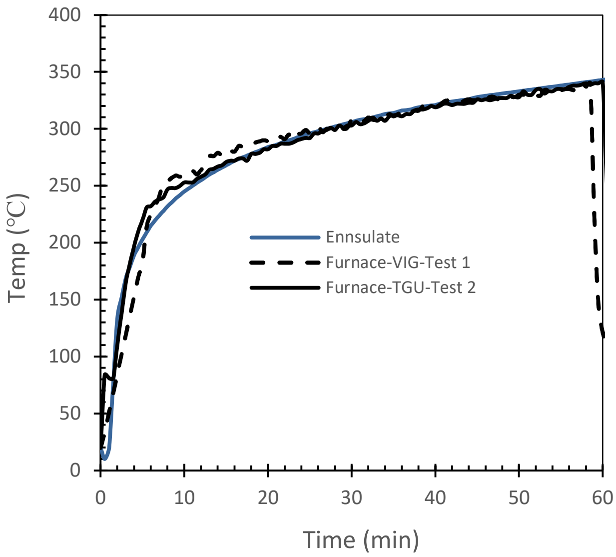


Figure 33 - Batch 1 design fire vs furnace fire

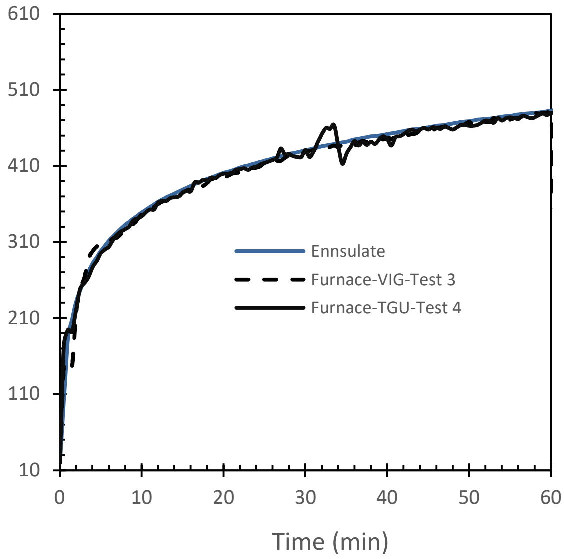


Figure 34 - Batch 2 design fire vs furnace fire

- 1st Batch Test

The temperature versus time plots from the first two tests are superimposed in Figure 35 below for comparison purposes. Both specimens were exposed to 35% of the standard ISO 834 fire curve for sixty minutes. For the VIG module, the graph shows that temperature readings from all the thermocouples remained relatively steady within the ambient temperature regions up to about twenty minutes into the test before a noticeable rise occurred. TC2 and TC7 recorded the highest and lowest temperatures on the unexposed sides respectively with a difference of about 23.5 °C at the end of the test.

For the TGU units, the largest variation in the recorded temperatures was 14 °C, with the highest and lowest temperature readings coming from TC2 and TC3, respectively. It can also be observed that the temperature readings from most of the thermocouples remained at ambient up to around 30 minutes when a rise occurred. However, this was a more gradual rise compared to the steeper profile seen in the VIG module. A difference of about 117 °C can be seen in the readings from TC2 for the VIG and TGU modules suggesting that the heat loss for the TGU module occurred at a slower rate than that for the VIG module. The readings from the radiometer showed a negligible heat flux for the entire duration of the tests for these panels.

In Figure 36, the readings from TCs 10 to TC 13 are presented. These thermocouples were installed on the spandrel. The plots show that there is no noticeable difference in the readings for the VIG and TGU modules. The curves stayed relatively flat within ambient temperature for the duration of the tests.

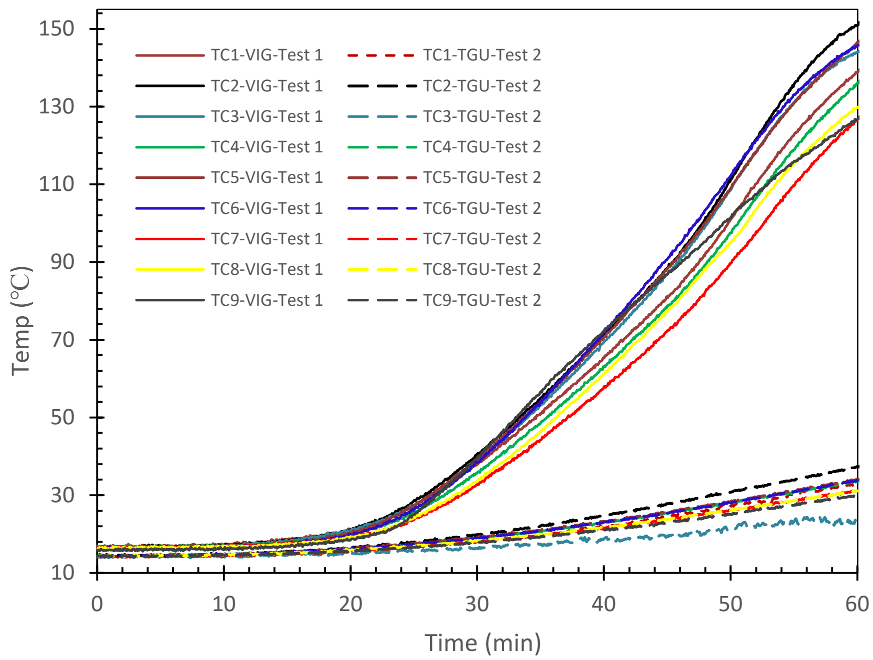


Figure 35 - Batch 1 thermocouple data (unexposed glass surface)

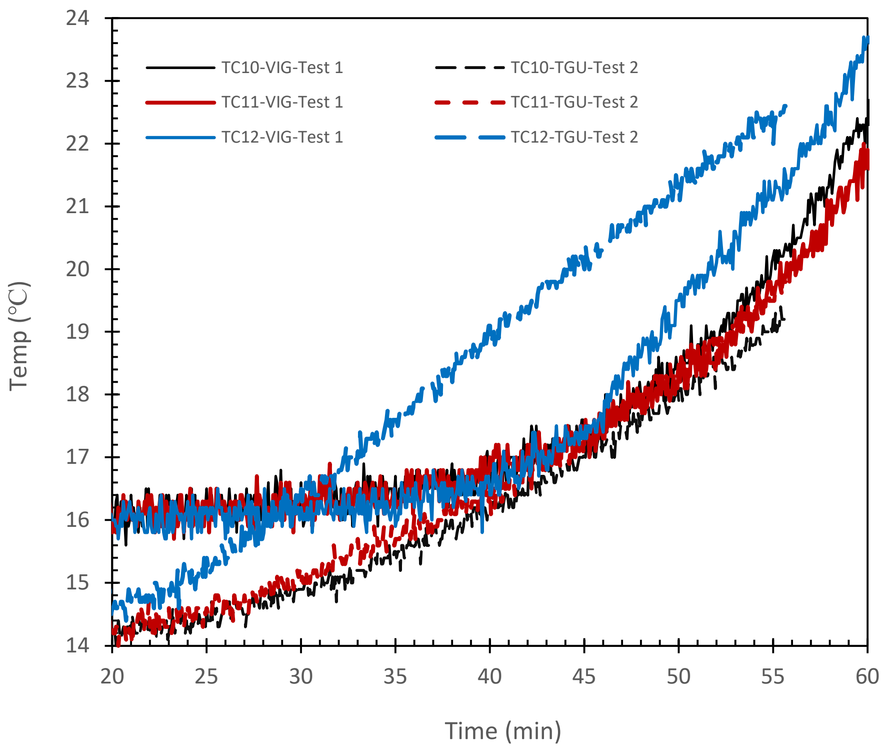


Figure 36 - Batch 1 thermocouple data (unexposed spandrel)

Selected pictures of the post-heating condition of tests 1 and 2 are presented in Figure 37 and Figure 38. Major observation is that cracks occurred in the TGU model at about twenty-seven minutes into the heating, however, no cracks were seen in the VIG module. The cracks began in the top left corner of the module and progressively propagated towards the other parts Figure 39.

Figure 37 - Post test condition VIG-T1

Figure 38 - Post test condition TGU-T2

Figure 39 - Crack propagation TGU-T2

The presence of the cracks seems to have had a negligible effect on the temperatures of the unexposed side of the panel as no unusual rise in the temperature readings was observed.

- 2nd Batch Test

The specimens in tests 3 and 4 were subjected to a higher temperature (50% of ISO 834 fire curve) upon completion of the first batch tests. The goal was to check if the behaviour observed in the first set of tests would be replicated under a higher temperature regime. The results from the tests show that for the most part, the responses were consistent with those seen in tests 1 and 2. For the VIG module, the rise in the temperature readings on the unexposed side of the module began just before five minutes post heating. At the end of the sixty minutes, highest and lowest temperatures of 231 and 203 ^{o}C were recorded in TC 3 and TC 9, respectively. However, temperatures in the TGU module remained rather steady at ambient up to about thirty minutes after which a noticeable increase was observed.

For the TGU units, the largest variation in the recorded temperatures was 15 ℃ compared to the 28 ^{o}C observed in the VIG module, with the highest and lowest temperature readings coming from TC3 and TC4. As in the previous case, the heat loss for the TGU module occurred at a slower rate when compared with the VIG module. For instance, the disparity in TC3 readings between the VIG and TGU units is about 167 ^{o}C. Furthermore, the heat flux measured by the radiometer was insignificant. The plots from the thermocouples installed on the spandrels are presented in Figure 40. These plots reveal negligible differences in the temperature readings.

At about 28 minutes post heating, flames appeared at the upper right corner of the TGU panel and lasted for about twenty minutes afterwards as shown in Figure 42 and Figure 43. Pictures of the specimens upon dismantling from the furnace are provided in Figure 44 and Figure 45. It can be observed that whilst the VIG module witnessed some pronounced staining no visible cracks occurred unlike the TGU modules where significant cracks and localised fracture of the glass material occurred. A close-up view of a fractured section of the panel is shown in Figure 46.

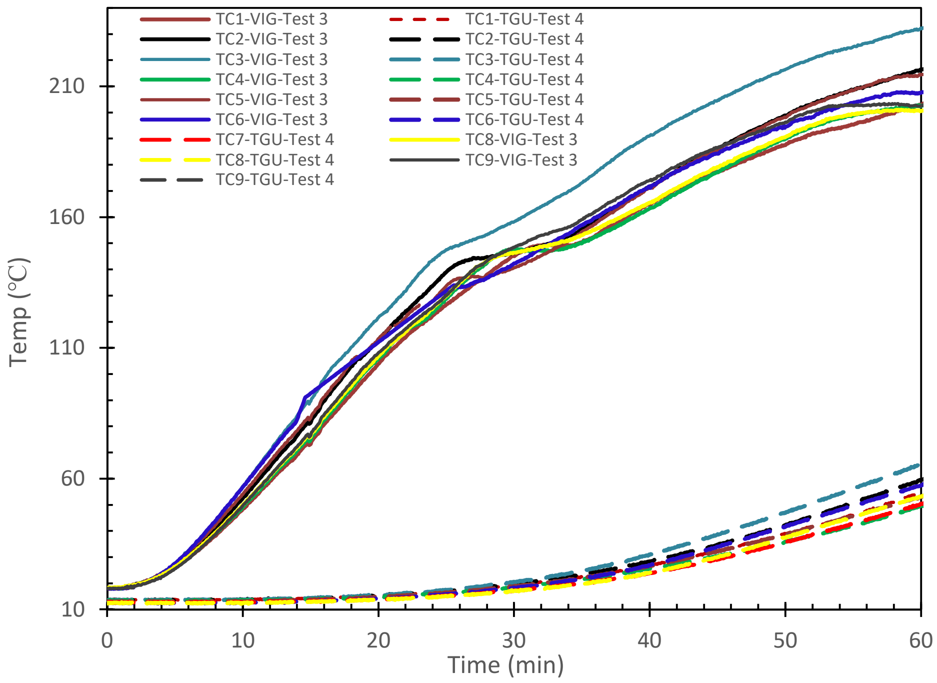


Figure 40 - Batch 2 thermocouple data (unexposed glass surface)

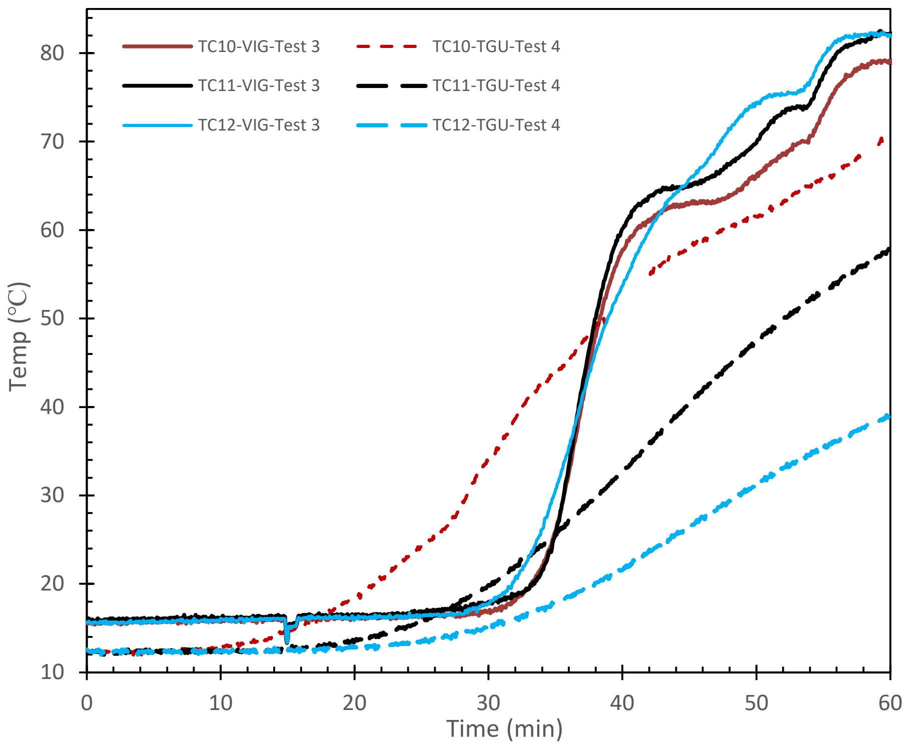


Figure 41 - Batch 2 thermocouple data (unexposed spandrel)

Figure 42 - Flame initiation TGU-T4

Figure 43 - Flame propagation TGU-T4

Figure 44 - Post test condition VIG-T3

Figure 45 - Post test condition TGU-T4

Figure 46 - TGU-T4 fractured glass

4.3.4 FMU results

The results from the tests seem to suggest that the TGU performed better than the VIG modules as the rate of heat loss in the former was consistently lower than in the latter for all the tests. This may be attributed to the fact that the thickness of the TGU modules was about double that of the VIG modules. i.e., 47.5mm versus 24.8mm. Readings from the radiometer gave negligible heat flux across the panels for all the tests conducted.

The tests showed that resistance of the EENSULATE facade (glass included) is not critical, and it has preserved its integrity during the test, perfectly in line with the expectations.

4.4 Non-destructive test

4.4.1 Introduction

The control of the foam filling process in the spandrel cavity is important to obtain a product with good thermal properties and guarantee the quality of the spandrel components.

In this activity, a non-destructive test bench was developed to control foam filling in the spandrel cavity. Inhomogeneities in this kind of low-density material are rather difficult to be identified with non-destructive methods. Preliminary tests were carried out on a sample that simulates the spandrel realized in the laboratory which consists of a sandwich component formed by a foam core and aluminium plates glued on the upper and lower side.

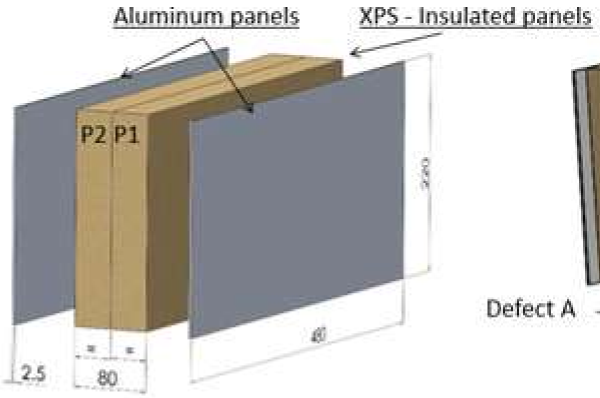
Ultrasound testing (US), Thermography (IRT) and Laser Ultrasonics (LUT) are the NDT techniques taken into consideration in the preliminary tests to evaluate their applicability in the control of the foam density distribution and fluctuation in the real spandrel.

TeraHertz imaging technique was not taken into consideration in the preliminary tests because it is not compatible with the materials that make up the spandrel and with the aluminium structure. Materials with large electrical conductivity (i.e., metals) or with large static dipoles (e.g., water) tend to be strong absorbers, which can provide a source of contrast in image formation[2].

4.4.2 Test in preliminary item

The sample consists of two XPS-insulated panels glued for a total thickness of 80 mm and two 2.5 mm aluminium sheets glued sideways. The XPS-insulated panels have a density of 32 kg/m3 according to the density value of the foam used to fill the cavities of the spandrel. The sample was used to evaluate the efficiency of US, IRT and LUT and to identify the most reliable technique to be used in the inspection of the spandrel produced in the EENSULATE project.

The sample was realised with some inner defects simulating areas where foam filling is missing. The dimensions of the sample and defects are shown in Figure 47



Defects	Type of defect
A	air gap between aluminium plate and insulated panel P1 – 5 mm thick
B	region without glue
C	air gap between insulated panel P1 and P2 - 5 mm thick

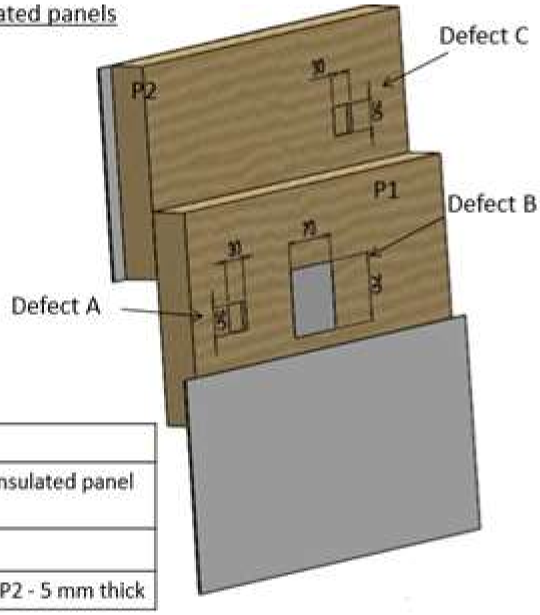
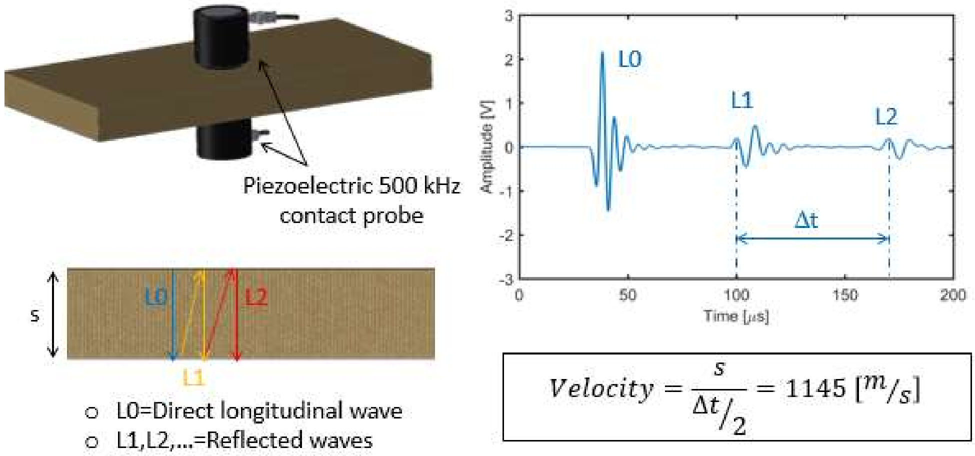


Figure 47 - Test samples

4.4.3 Ultrasound testing (US)

Ultrasonic testing is one of the most effective methods for detecting internal defects in structural components used in the construction sector[3]. The US method assumes that a crack, a lack of cohesion and a detachment of the material layers reduces the speed and amplitude of the ultrasonic waves. Two configurations were used in this study: pulse echo and through transmission mode.

The XPS-insulated panel was characterized by means of precise ultrasonic velocity measurements (see Figure 48) to calculate the speed of the ultrasonic wave which is 1145 m/s.



$$Velocity = \frac{s}{\Delta t/_2} = 1145\ [^m/_s]$$

Figure 48 - Ultrasound speed measurements in XPS – insulated panel.

4.4.4 Through transmission model

The tested specimens were placed on a workbench with a 1-axis scanning system for probe motion. The two ultrasonic probes were horizontally aligned and moved in one longitudinal direction with a spatial resolution of 5 mm.

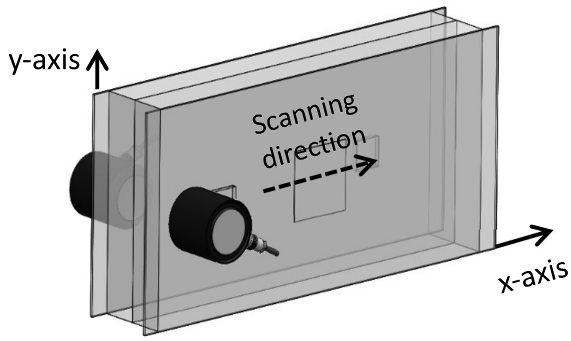


Figure 49 - The UT experimental set-up - Through transmission mode

The dedicated measurement chain proposed is composed of the following equipment:

- DPR300 pulser and receiver:

Type of emitted ultrasonic signal: spike, duration 10–70 ns.
Max excitation voltage: 900V pk.

- Digitizer NI PCI 5122 acquisition board:

Channels simultaneously sampled at 14-bit resolution.
100 MS/s real-time.
100 MHz bandwidth.

- 2 piezoelectric 500 kHz contact probes (active area of 32mm).

The voltage signals in time domain (Figure 50) were acquired with a sample rate of 50 MHz (acquisition time 200 us) and for improving the SNR at each measurement point, 200 averages were performed. The arrival of the longitudinal wave (LO) is evident in the time history.

In through transmission mode the defect is well detected. Figure 50 show the plot of both root mean square (RMS) amplitude and the B-scan close-up around the longitudinal wave time of arrival, where the defects are clearly well detected. The RMS plot is derived from the Bscan represented in Figure 50 a by integrating the data along the time axis and normalizing with respect to the maximum value.

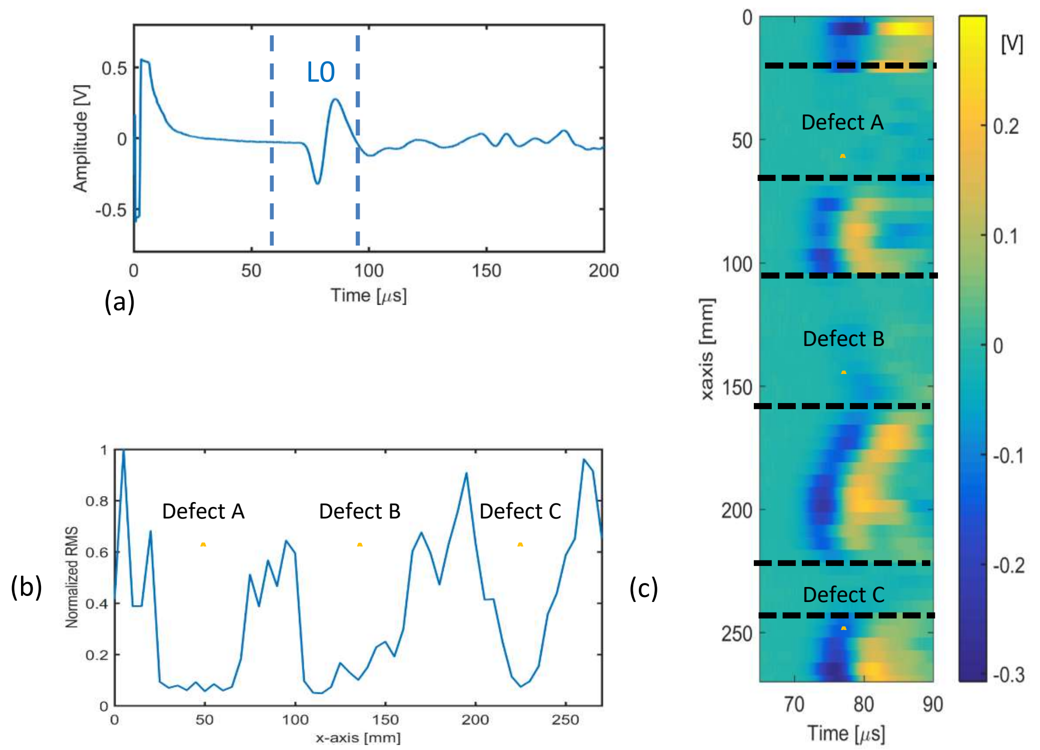


Figure 50 - (a) The ultrasound signal in the time domain, (b) Normalized RMS and (c) B-scan close-up around the longitudinal wave time of arrival.

4.4.5 Pulse echo model

In this case a single probe at 500 kHz was moved with the linear scanning system with a spatial resolution of 10 mm (see Figure 51).

Figure 51 - The UT experimental set-up – Pulse echo mode.

Figure 52 (a) shows the ultrasound signal in the time domain achieved by pulse echo inspection. RMS normalized amplitude and the B-scan map close-up around the longitudinal wave time of arrival are shown, respectively, in Figure 52 (b and c).

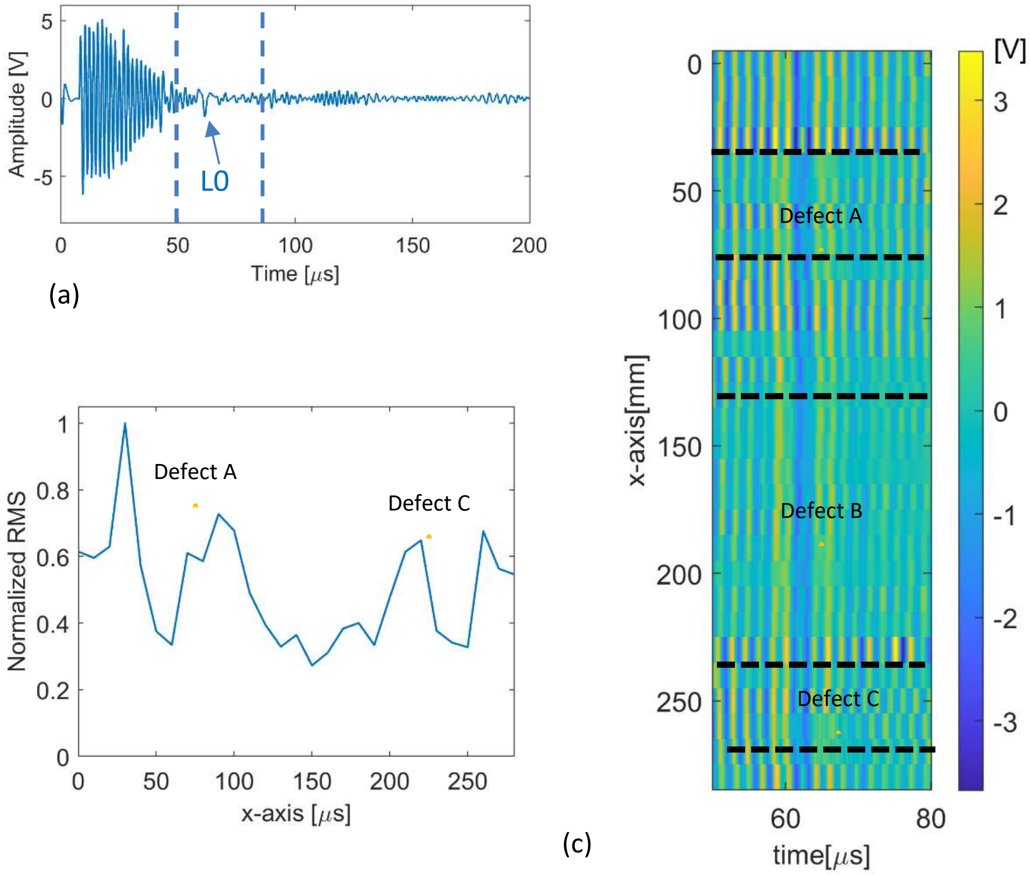


Figure 52 - The ultrasound signal in the time domain, (b) Normalized RMS and (c) B-scan close-up around the longitudinal wave time of arrival.

4.4.6 Laser Ultrasonics (LUT)

The laser ultrasonics procedure is based on high energy pulsed laser for generation of ultrasonic waves and then ultrasound contact probe for detecting the waves[4], [5].The generation of ultrasonic waves into the material is since the laser impinging on the surface creates a transient increase in temperature in a small volume of material causing a thermo elastic expansion and thus propagation of elastic waves.

The laser ultrasonic system was made up of a pulsed laser source, a Nd-Yag IR laser (1064 nm), emitting pulses of 12 ns duration and 82 mJ energy, from Continuum, and a 500 kHz ultrasound contact piezoelectric probe from Olympus (32 mm diameter of active area). The ultrasound probe conditioning system was a DPR 300 Pulser/Receiver from JSR Ultrasonics. Ultrasound signals were amplified with a gain level of 69 dB and acquired with a high-speed Digitizer board NI PXI-5122 (100 MHz bandwidth).

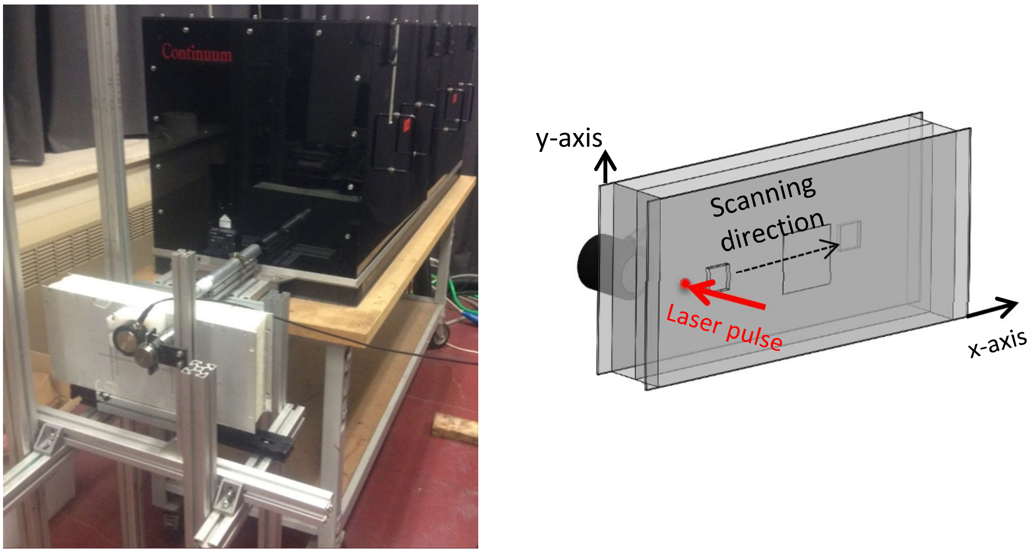


Figure 53 - The Laser Ultrasonics experimental set-up.

The laser beam was guided towards the sample under test by means of a tube connected to the pulsed laser cavity as shown in Figure 53. The laser source and the receiving probe were aligned horizontally on the two sides of the sample respectively and moved in the longitudinal direction by a linear scanning system. A collimated laser beam with a diameter of about 6 mm was used to maintain the generation of ultrasonic waves in a thermoelastic regime. The results obtained are reported hereafter. Figure 54 shows the ultrasound signal in the time domain achieved by laser ultrasonic inspection. RMS normalized amplitude and the B-scan map close-up around the longitudinal wave time of arrival are shown, respectively, in Figure 54. The defects are clearly detected.

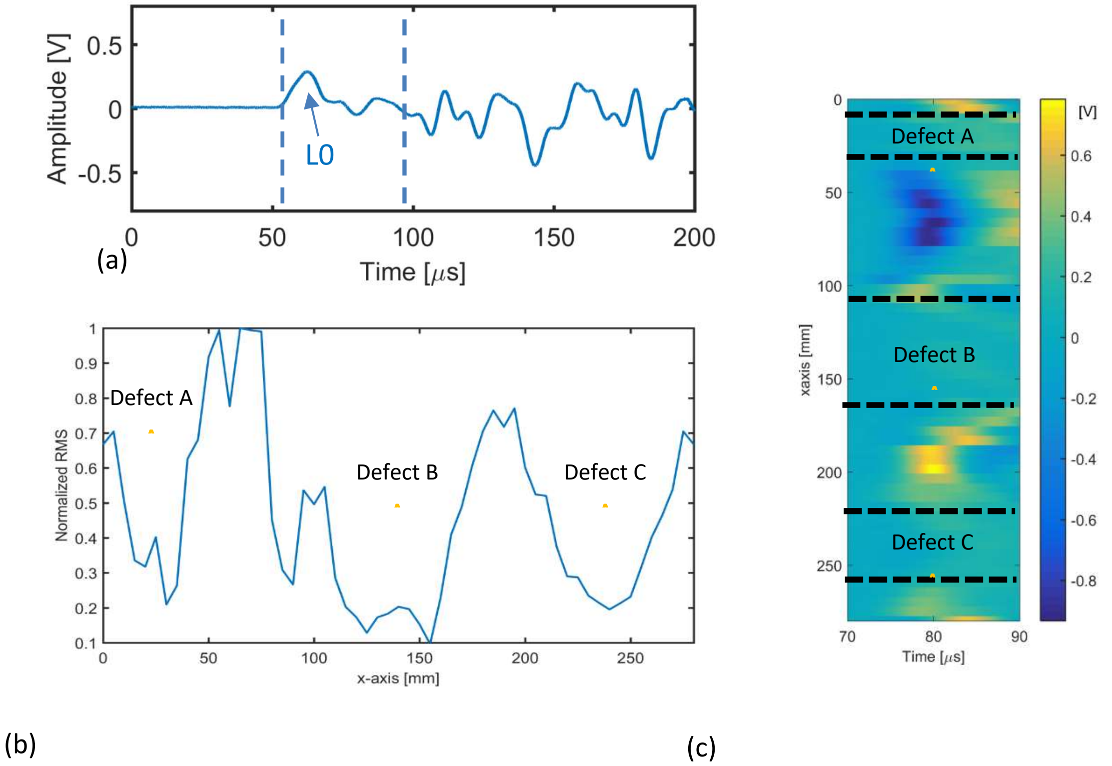


Figure 54 - (a) The ultrasound signal in the time domain, (b) Normalized RMS and (c) B-scan close-up around the longitudinal wave time of arrival

4.4.7 Infrared Thermography (IRT)

The IRT method assumes that for temperatures above absolute zero all the objects emit energy from their surface in the form of thermal radiation. Thermograph equipment captures the IR radiation and converts it to a thermal image (thermogram), which represents the distribution of surface temperature of the object. The IRT can be classified in two categories:

- passive methods, for which no additional artificial source of heat is used.
- active methods: for which the diffusion of heat is provoked by artificial means.

IRT allows observing a field of temperature on a surface. The information is extracted from gradients observed at the surface at one time. Information may also be deduced from evolutions of the temperature field with time. Temperature gradients or variations can only be observed if the system is submitted to heat transfer.

The active method was used for the sample inspection and the following equipment was used:

- 4 halogen lamps 220 V, 1000 W,
- Infrared camera from InfraTec (Microbolometer detector with (1,024 x 768 pixel) IR and Temperature resolution @ 30 °C better than 0.05 K).
- Irbis III software (for film capture and results visualization/analysis).

The tests were carried out by setting a frame rate of 1Hz and acquiring 400 images for a total time of 6,66 minutes. An example of thermogram (thermal map showing the emissivity distribution of the sample surface) is given in Figure 55 and Figure 56. Defects are not detectable. One of the main causes of the inefficiency of the thermographic technique is the high reflectivity of the aluminum panel which hinder the heat propagation in the material underneath.

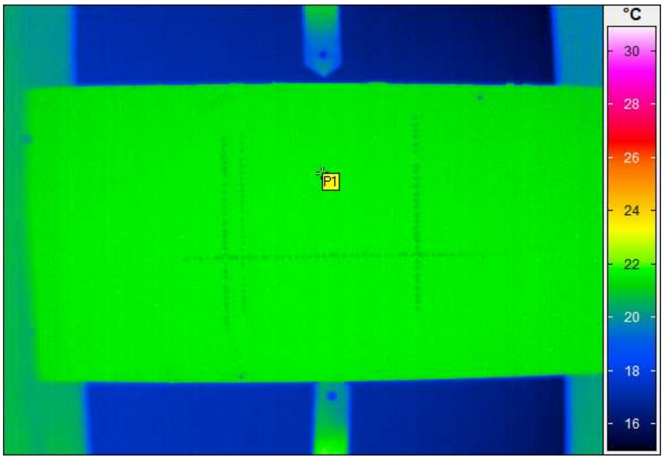


Figure 55 - Thermal mapping provided by IR thermography

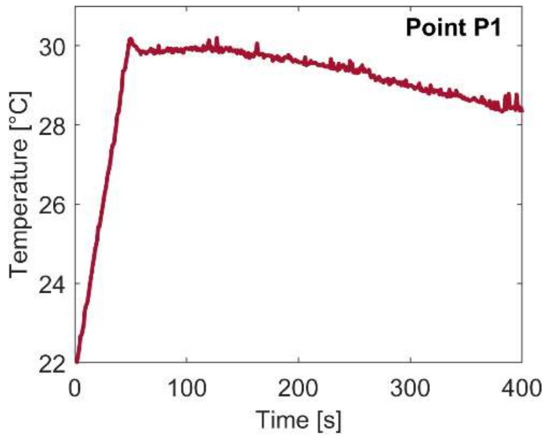


Figure 56 - temperature profile evaluated at point P1

4.4.8 EENSULATE spandrel

Preliminary tests carried out on the sample showed that the standard ultrasound technique (UT) and laser ultrasonics (LUT) are the most effective techniques.

Given the high cost of the LUT technique, the UT technique was chosen for the design of the test bench for the EENSULATE spandrel controls. The pulse eco mode configuration was preferred as it allows access only from one side, avoiding problems of high attenuation of the ultrasound signal in the stratigraphy of the spandrel (see Figure 57). The inspection was performed from external side where there is only the glass of 6 mm before the foam.

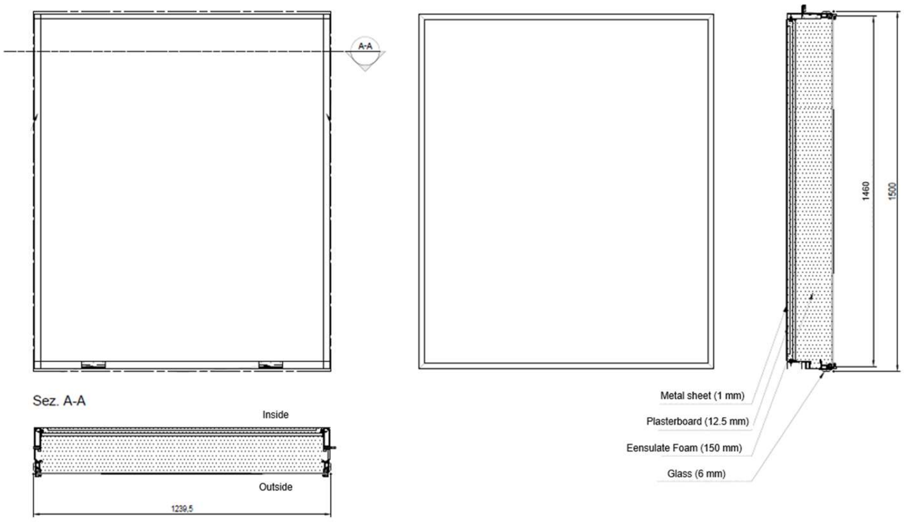


Figure 57 - Spandrel stratigraphy

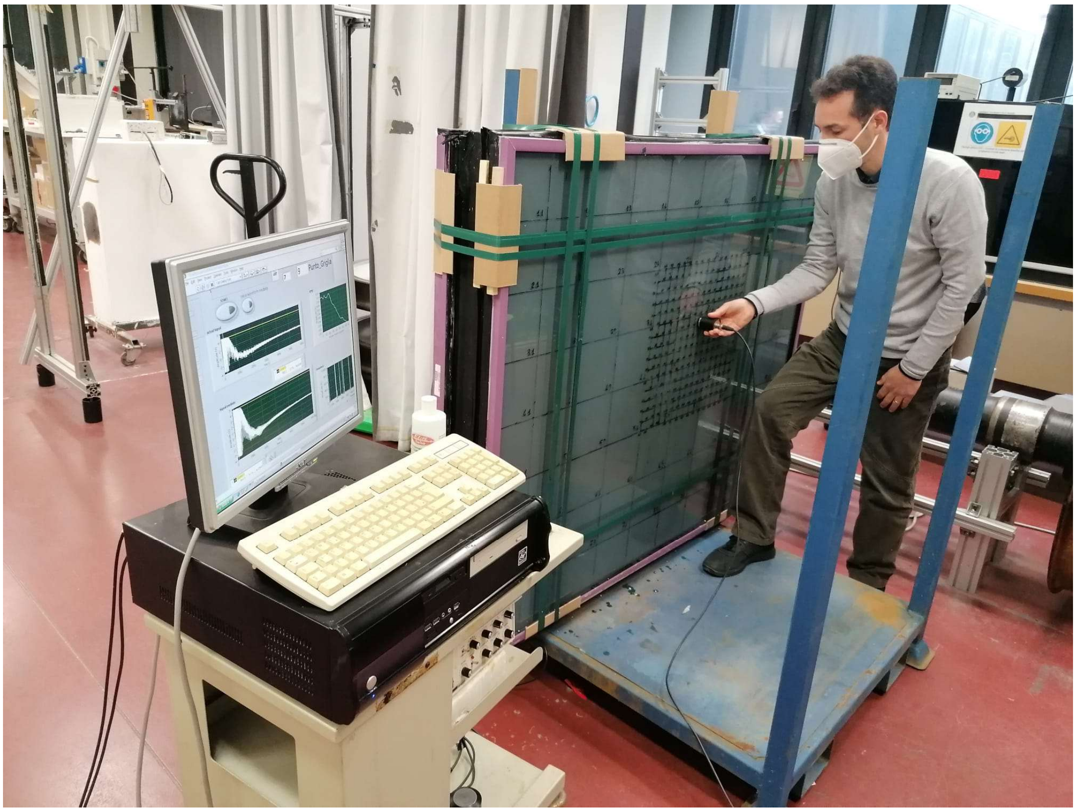


Figure 58 - The experimental set-up used for EENSULATE spandrel test.

500 kHz ultrasonic probe in pulse echo mode was moved in two orthogonal directions with a spatial resolution of 150 mm to inspect an area of 1350 × 1050 mm^2 with a grid of 7 rows and 9 columns. A time history of the US time history measured in one point of the grid is reported in Figure 59.

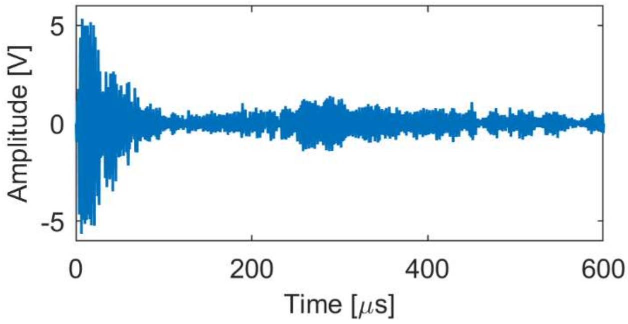


Figure 59 - The ultrasound signal in the time domain.

Figure 60 shows the C-scan maps obtained by the contact pulse echo configuration. The map reports the RMS signal amplitude, which is thus proportional to attenuation. The map shows how the density distribution of the foam is uniform within the spandrel. The edge effects evident from the map are due to multiple reflections occurring at the edge of the sample.

Figure 61 shows a C-scan map obtained by scanning an area of 480x480 mm^2 with a spatial resolution of 30 mm to eliminate scattering phenomena due to the proximity of the probe to the edges of the spandrel.

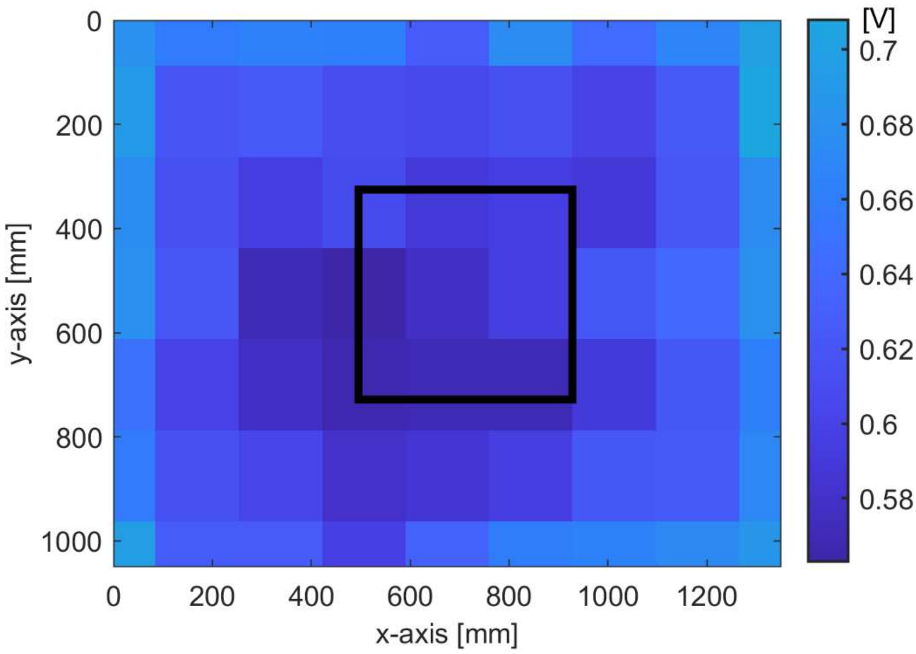


Figure 60 - C-Scan map, pulse echo mode 500 kHz probe: inspection area of 1350x1050 mm^2 and resolution of 150 mm,

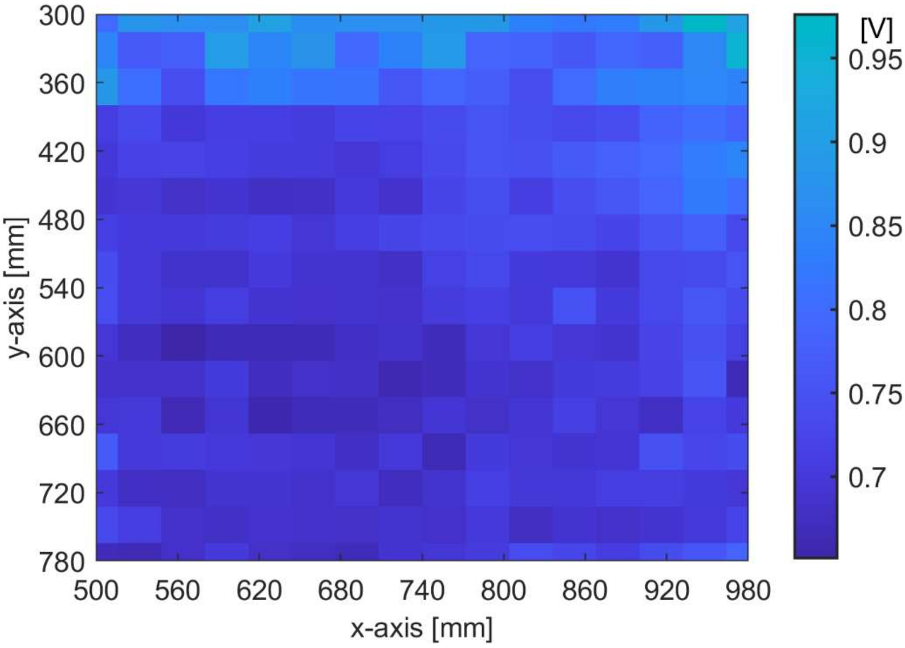


Figure 61 - C-Scan map, pulse echo mode 500 kHz probe: inspection area of 480x480 mm^2 and resolution of 30 mm

5 Conclusions

The tests conducted on EENSULATE façade demonstrate the effectiveness of the solution designed, manufactured, and installed. The integration of the EENSULATE technologies in a real façade demonstrates the positive result for market application. In particular:

- The foam and the VIG have been fully integrated and tested in the EENSULATE façade demonstrating the correctness of manufacturing processes both for VIG (laminated) as well as spandrel foaming;

- The EENSULATE façade achieves the performances (water, air tightness, wind resistance), safety requirements (impact resistance), acoustic insulation and fire reaction in line with market expectations and compelling with the norms;

- The EENSULATE façade passed the tests, demonstrating its effectiveness also in comparison with market benchmark (façade with mineral wool and TGU);

The overall objectives expected by EENSULATE façade system are considered achieved opening to market application.

6 References

[1] «UNI EN 13830:2020». http://store.uni.com/catalogo/uni-en-13830-2020 (consultato apr. 29, 2021).

[2] B. B. Hu e M. C. Nuss, «Imaging with terahertz waves», *Opt. Lett.*, vol. 20, n. 16, pagg. 1716–1718, ago. 1995, doi: 10.1364/OL.20.001716.

[3] G. M. Revel, G. Pandarese, e A. Cavuto, «Advanced ultrasonic non-destructive testing for damage detection on thick and curved composite elements for constructions», *J. Sandw. Struct. Mater.*, vol. 15, n. 1, pagg. 5–24, gen. 2013, doi: 10.1177/1099636212456861.

[4] C. C. Chia, H.-M. Jeong, J.-R. Lee, e G. Park, «Composite aircraft debonding visualization by laser ultrasonic scanning excitation and integrated piezoelectric sensing», *Struct. Control Health Monit.*, vol. 19, n. 7, pagg. 605–620, 2012, doi: https://doi.org/10.1002/stc.1504.

[5] G. M. Revel, A. Cavuto, e G. Pandarese, «Laser ultrasonics for bulk-density distribution measurement on green ceramic tiles», *Rev. Sci. Instrum.*, vol. 87, n. 10, pag. 102504, ott. 2016, doi: 10.1063/1.4964626.