

2017-2020

# PROGRESS

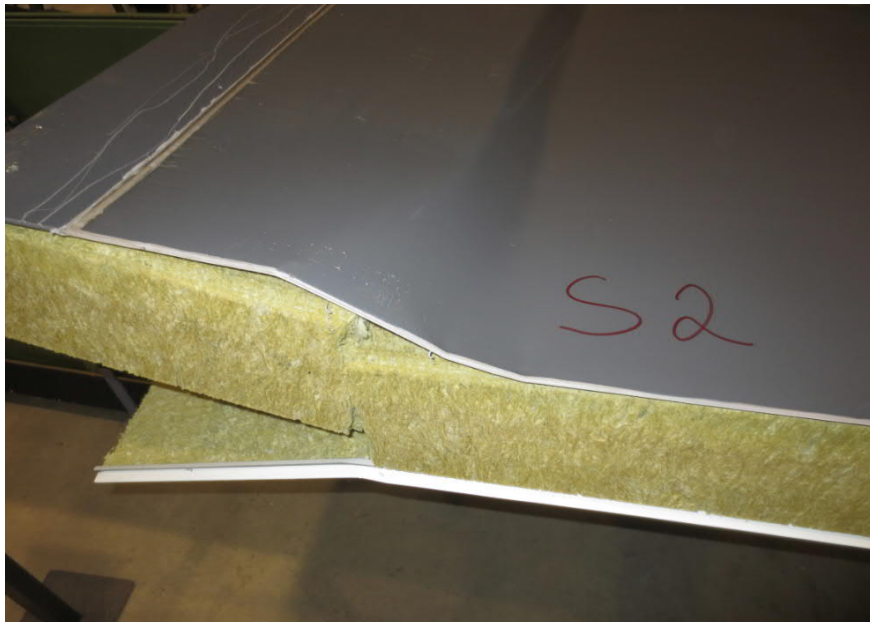
PROVISIONS FOR GREATER REUSE OF STEEL STRUCTURES

Research Fund for Coal and Steel  
Grant agreement No: 747847



## Report on testing of materials and products

February 2020



Deliverable: D7.1b Report on testing of materials and products

Confidentiality: Public

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## Executive summary

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This report is the deliverable D7.1b of the PROGRESS project (Provisions for Greater Reuse of Steel Structures) and covers the second part of Task 7.1 of the project Grant Agreement, namely the following topics:

- verification of the mechanical properties of the load-bearing structure (frames, secondary elements) after the deconstruction in Section 2.2,
- verification of the chemical properties of the load-bearing structure in Section 2.3, and
- verification of the quality of the envelope in Section 3.

The objective of the work reported in this document is to demonstrate the technical performance and efficiency of the testing methods and strategies for re-use of single-storey building components. The verification/testing methods are to be demonstrated on the materials and components removed from the existing buildings. The main aim is to review the processes needed if re-used components are going to be used in the new building in order to show to investors the supposed competitiveness of steel buildings due to their high technical reusability compared to different solutions.

The protocol for sampling and interpretation of material properties for the relevant certification is presented in PROGRESS deliverable D2.3 “Quality verification protocol including test results” [1] and the purpose of this document is to benchmark the experimental methods referred in [1]. Their complete overview is in Section 0 of this document and the complementary material is provided in the Annexes.

The materials and components for testing were obtained from different existing buildings of various age (12 to 70 years) and climate exposure (Romania, Germany, Finland) and tested in several laboratories (e.g. RWTH Aachen University, Universitatea Politehnica Timișoara, VTT Technical Research Centre of Finland).

## Contents

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|                                                                       |    |
|-----------------------------------------------------------------------|----|
| Executive summary.....                                                | 3  |
| Contents .....                                                        | 4  |
| 1 Introduction .....                                                  | 5  |
| 1.1 Overview of the tests.....                                        | 5  |
| 2 Verification of the quality of structural elements.....             | 8  |
| 2.1 Test specimens.....                                               | 8  |
| 2.1.1 Steel bars.....                                                 | 8  |
| 2.1.2 Structural steel I-profiles.....                                | 8  |
| 2.1.3 Structural steel angle.....                                     | 9  |
| 2.2 Testing of mechanical properties.....                             | 10 |
| 2.2.1 Tensile tests .....                                             | 10 |
| 2.2.2 Small punch tests .....                                         | 12 |
| 2.2.3 Instrumented indentation testing.....                           | 15 |
| 2.2.4 Sub-sized impact toughness testing .....                        | 18 |
| 2.2.5 Hardness testing .....                                          | 18 |
| 2.2.6 Summary of mechanical testing.....                              | 19 |
| 2.3 Testing of chemical properties.....                               | 22 |
| 3 Verification of the quality of the envelope .....                   | 24 |
| 3.1 Test specimens.....                                               | 24 |
| 3.1.1 Mineral wool (MW) panels.....                                   | 24 |
| 3.1.2 Polyurethane (PIR) panels.....                                  | 26 |
| 3.1.3 One-sided fasteners .....                                       | 28 |
| 3.2 Structural tests .....                                            | 29 |
| 3.2.1 Density of the core material.....                               | 29 |
| 3.2.2 Compression tests.....                                          | 30 |
| 3.2.3 Tensile tests.....                                              | 31 |
| 3.2.4 Bending tests .....                                             | 33 |
| 3.2.5 Shear tests.....                                                | 34 |
| 3.3 Tests on mechanical fasteners to one face of sandwich panel ..... | 35 |
| 3.4 Thermal resistance/conductivity (lambda) tests.....               | 38 |
| 4 Summary and conclusions.....                                        | 39 |
| References .....                                                      | 40 |
| Annex A Small punch tests results.....                                | 41 |
| Annex B Sandwich panels mechanical testing results.....               | 45 |
| Annex C Analysis of structural testing of sandwich panels.....        | 58 |
| Annex D Photographs.....                                              | 60 |

## 1 Introduction

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The objective of the work reported in this document is to demonstrate the technical performance and efficiency of the testing methods and strategies for re-use of single-storey building components. The verification/testing methods are to be demonstrated on the materials and components removed from the existing buildings. The main aim is to review the processes needed if re-used components are going to be used in the new building in order to show to investors the supposed competitiveness of steel buildings due to their high technical reusability compared to different solutions.

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The materials and components for testing were obtained from different existing buildings of various age (12 to 70 years) and climate exposure (Romania, Germany, Finland) and tested in several laboratories (e.g. RWTH Aachen University, Universitatea Politehnica Timișoara, VTT Technical Research Centre of Finland).

### 1.1 Overview of the tests

The following text summarizes the number and types of experiments conducted on structural steelwork and envelopes recovered from single-storey steel buildings as well as the reference experiments on new materials. The specimens are labelled according to the component type and (if needed) the location of the extraction from the components.

#### Component types

- ST – Structural steel component
  - ST-B – steel bar (tie or stud) tested in SCIENCE project in 2013
  - ST-P – steel I-section removed from the steel hall in Romania in 2019
    - ST-P-I – web of the I-section
    - ST-P-T – flange of the I-section
    - ST-P-X – intermediate area between the web and the flange
  - ST-C – steel angle removed from the steel hall in Germany in 2018
- MW – Mineral wool sandwich panel
  - MW-N – panel removed from the north side of the building in Finland
  - MW-S – panel removed from the south side of the building in Finland
  - MW-Ref – reference (new) panel tested in 2007
- PIR – Polyurethane wool sandwich panel
  - PIR-S – panel removed from the south side of the Cube demo building in Aachen
  - PIR-W – panel removed from the west side of the Cube demo building in Aachen

The overview of mechanical, chemical and other tests reported in this document is presented in Table 1. It should be noted that some results for the reference materials (e.g. bars and MW panels) were obtained from the previous work by the project partners.

Table 1. Overview of the tests

| Sample | Test type                       | Number of tests   | Year | Standard(s)             |
|--------|---------------------------------|-------------------|------|-------------------------|
| ST-B1  | tensile test                    | (5) <sup>1</sup>  | 2013 | EN 10002-1              |
|        | small punch test                | 4                 | 2019 | prEN 15627              |
| ST-B2  | tensile test                    | (5) <sup>1</sup>  | 2013 | EN 10002-1              |
|        | small punch test                | 4                 | 2019 | prEN 15627              |
| ST-P1  | tensile test                    | 6                 | 2019 | EN ISO 6892-1           |
|        | small punch test                | 6                 | 2020 | prEN 15627              |
|        | instrumented indentation test   | 2                 | 2020 | -                       |
|        | sub-sized impact toughness test | 4                 | 2020 | -                       |
|        | hardness test                   | 25                | 2020 | -                       |
| ST-P2  | tensile test                    | 4                 | 2019 | EN ISO 6892-1           |
| ST-P3  | tensile test                    | 4                 | 2019 | EN ISO 6892-1           |
| ST-C   | tensile test                    | 1                 | 2018 | EN ISO 6892-1, method B |
|        | impact test at room temperature | 1                 | 2018 | EN ISO 148-1            |
|        | chemical test                   | 1                 | 2018 | -                       |
| MW-Ref | measurement of density          | (6) <sup>1</sup>  | 2007 | EN 14509                |
|        | compression test                | (10) <sup>1</sup> | 2007 | EN 14509                |
|        | tensile test                    | (10) <sup>1</sup> | 2007 | EN 14509                |
|        | bending test                    | (5) <sup>1</sup>  | 2007 | EN 14509                |
|        | shear test                      | (9) <sup>1</sup>  | 2007 | EN 14509                |
| MW-S1  | measurement of density          | 6                 | 2018 | EN 14509                |
|        | compression test                | 5                 | 2018 | EN 14509                |
|        | tensile test                    | 5                 | 2018 | EN 14509                |
|        | shear test                      | 1                 | 2018 | EN 14509                |
|        | tensile test of fastener        | 5                 | 2018 | -                       |
| MW-S2  | measurement of density          | 6                 | 2018 | EN 14509                |
|        | shear test                      | 1                 | 2018 | EN 14509                |
| MW-S3  | measurement of density          | 6                 | 2018 | EN 14509                |
|        | compression test                | 5                 | 2018 | EN 14509                |
|        | tensile test                    | 5                 | 2018 | EN 14509                |
|        | shear test of fastener          | 3                 | 2018 | -                       |
| MW-S6  | measurement of density          | 6                 | 2018 | EN 14509                |
|        | compression test                | 5                 | 2018 | EN 14509                |
|        | tensile test                    | 5                 | 2018 | EN 14509                |

|                              |                          |                              |      |                    |
|------------------------------|--------------------------|------------------------------|------|--------------------|
| MW-S7                        | measurement of density   | 6                            | 2018 | EN 14509           |
|                              | compression test         | 5                            | 2018 | EN 14509           |
|                              | tensile test             | 5                            | 2018 | EN 14509           |
|                              | shear test               | 1                            | 2018 | EN 14509           |
|                              | thermal resistance test  | 2                            | 2018 | EN 12667, ISO 8301 |
| MW-S8                        | measurement of density   | 6                            | 2018 | EN 14509           |
|                              | compression test         | 5                            | 2018 | EN 14509           |
|                              | tensile test             | 5                            | 2018 | EN 14509           |
| MW-N4                        | measurement of density   | 6                            | 2018 | EN 14509           |
|                              | compression test         | 5                            | 2018 | EN 14509           |
|                              | tensile test             | 5                            | 2018 | EN 14509           |
|                              | shear test of fastener   | 5                            | 2018 | -                  |
|                              | tensile test of fastener | 5                            | 2018 | -                  |
|                              | thermal resistance test  | 1                            | 2018 | EN 12667, ISO 8301 |
| MW-N2                        | bending test             | 1                            | 2018 | EN 14509           |
| MW-N3                        | bending test             | 1                            | 2018 | EN 14509           |
| MW-N5                        | measurement of density   | 6                            | 2018 | EN 14509           |
|                              | compression test         | 5                            | 2018 | EN 14509           |
|                              | tensile test             | 5                            | 2018 | EN 14509           |
| MW-N6                        | measurement of density   | 6                            | 2018 | EN 14509           |
|                              | compression test         | 5                            | 2018 | EN 14509           |
|                              | tensile test             | 5                            | 2018 | EN 14509           |
|                              | bending test             | 1                            | 2018 | EN 14509           |
| PIR-S1                       | bending test             | 1                            | 2020 | EN 14509           |
| PIR-S2                       | bending test             | 1                            | 2020 | EN 14509           |
| PIR-S3                       | compression test         | 7                            | 2020 | EN 14509           |
|                              | tensile test             | 7                            | 2020 | EN 14509           |
| PIR-S6                       | shear test               | 7                            | 2020 | EN 14509           |
| PIR-W1                       | bending test             | 1                            | 2020 | EN 14509           |
| PIR-W2                       | bending test             | 1                            | 2020 | EN 14509           |
| PIR-W3                       | compression test         | 7                            | 2020 | EN 14509           |
|                              | tensile test             | 7                            | 2020 | EN 14509           |
| PIR-W5                       | shear test               | 7                            | 2020 | EN 14509           |
| <b>Total number of tests</b> |                          | <b>269 (+50)<sup>1</sup></b> |      |                    |

<sup>1</sup> Test results were obtained from the previous work

## 2 Verification of the quality of structural elements

### 2.1 Test specimens

The test programme for structural elements presented in this section covers structural steel elements from hot-rolled and cold-worked steel produced after 1970's that are supposed to be performing well according to the current standards, and a steel element from 1930's which was especially tested to conform to the strength, toughness and weldability criteria.

#### 2.1.1 Steel bars

Two tensile test specimens made from structural steel grade S355 named *ST-B1* and *ST-B2* were delivered in the PROGRESS project for blind tests by Small Punch and nanoindentation test methods. The specimen designated *ST-B1* corresponds to the specimen 1 from 24 mm stud (Figure 1 left) and *ST-B2* corresponds to the specimen 2 made from 18 mm tie (Figure 1 right). Specimen *ST-B2* was cold worked to a higher strength as can be seen from the tensile test results in Section 2.2.1.



Figure 1 Tensile test specimens *ST-B1* (first on the left) and *ST-B2* (second on the right)

The tensile specimens were tested to rupture in SCIENCE project [2], and one grip end was given for Small Punch testing while the other end went to nanoindentation testing. The grip ends were cylindrical with diameter 20 mm in *ST-B1* and 18 mm in *ST-B2* and the tensile test was performed in hydraulic grips.

The purpose of this testing exercise was to demonstrate miniature-testing methods for validation of dismantled building frame beams. The benefit of miniature methods is that the required sample size is so small that it can be removed from the surface of the component by not compromising the integrity of the component.

#### 2.1.2 Structural steel I-profiles

Four specimens from hot-rolled structural steel sections were prepared for the mechanical testing designated *ST-P1* to *ST-P4* (see Figure 2).



*Figure 2 Structural steel sections for the mechanical testing (from left to right)  
ST-P2, ST-P4 (not tested), ST-P1 and ST-P3*

### **2.1.3 Structural steel angle**

The last sample (ST-C) was tested separately as it was removed from the steel truss that was deconstructed for reuse. The purpose of the test was to check if the material's chemical composition allows the steel to be welded during the reuse process.



*Figure 3 Structural steel section for the chemical testing ST-C*

## 2.2 Testing of mechanical properties

This section summarizes the testing programme to determine mechanical properties of the steel extracted from the existing steelwork intended for reuse and the pilot tests made on steel stud and tie reused from the previous experimental programme. Two new minimal-invasive methods to determine tensile properties of steel were assessed and their results compared to standard coupon tests: small punch test and instrumented indentation tests.

### 2.2.1 Tensile tests

The basic properties of 24 mm structural stud *ST-B1* and 18 mm tie *ST-B2* were determined from coupon tests in accordance with EN 10002-1 'Metallic materials. Tensile testing. Part 1: Method of test (at ambient temperature)'. The results are presented in

Standard dog-bone coupons were extracted from the hot-rolled structural sections *ST-P1*, *ST-P2* and *ST-P3* and loaded with tensile displacement until the failure. The coupons extracted from the web are designated *ST-P1-I* to *ST-P3-I* and the coupons extracted from the flanges are designated *ST-P1-T* to *ST-P3-T*. The results of tensile tests of the structural steel hot-rolled sections are summarized in Table 4 and Table 5. The yield strength  $R_{p0.2}$  and the ultimate tensile strength  $R_m$  are in Table 4, and the elongation at maximum load  $A_{gt}$  and the elongation at failure are presented in Table 5. The results of the coupon test extracted from the structural steel angle *ST-C* are presented in Table 3.

Table 2 Tensile test results of round specimen - strength

|         | ST-B1               |                | ST-B2               |                |
|---------|---------------------|----------------|---------------------|----------------|
| Sample  | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] |
| 1       | 395*                | 541*           | 623                 | 674            |
| 2       | 389                 | 538            | 625*                | 673*           |
| 3       | 376                 | 538            | 624                 | 675            |
| 4       | 386                 | 543            | 625                 | 675            |
| 5       | 383                 | 543            | 623                 | 669            |
| Average | 386                 | 541            | 624                 | 673            |
| St.dev  | 6.3                 | 2.2            | 0.9                 | 2.2            |

\* specimen used for small punch and instrumented indentation testing

Table 3. Tensile test results of structural steel angle

|                                    | ST-C                |                |       |
|------------------------------------|---------------------|----------------|-------|
|                                    | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] | $A_t$ |
| Results of EN ISO 6892-1, method B | 338                 | 365            | 27.6% |
| USt 37-1 according to DIN EN 17100 | > 240               | 370 -450       | > 25% |

Table 4 Tensile test results of hot-rolled sections webs (I) and flanges (T) strength [MPa]

|         | ST-P1-I             |                | ST-P2-I             |                | ST-P3-I             |                |
|---------|---------------------|----------------|---------------------|----------------|---------------------|----------------|
| Sample  | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] | $R_{p0.2}$<br>[MPa] | $R_m$<br>[MPa] |
| 1       | 377                 | 506            | 355                 | 470            | 370                 | 481            |
| 2       | 376                 | 504            | 355                 | 475            | 364                 | 480            |
| 3       | 367                 | 507            | -                   | -              | -                   | -              |
| Average | 373                 | 506            | 355                 | 473            | 367                 | 481            |
| St.dev  | 4.5                 | 1.2            | 0.0                 | 2.5            | 3.0                 | 0.5            |
|         | ST-P1-T             |                | ST-P2-T             |                | ST-P3-T             |                |
| Sample  | $R_{p0.2}$          | $R_m$          | $R_{p0.2}$          | $R_m$          | $R_{p0.2}$          | $R_m$          |
| 1       | 357                 | 488            | 349                 | 482            | 384                 | 458            |
| 2       | 356                 | 483            | 366                 | 511            | 391                 | 471            |
| 3       | 351                 | 489            | -                   | -              | -                   | -              |
| Average | 355                 | 487            | 358                 | 497            | 388                 | 465            |
| St.dev  | 2.6                 | 2.6            | 8.5                 | 14.5           | 3.5                 | 6.5            |

Table 5 Tensile test results of hot-rolled sections webs (I) and flanges (T) elongation

|         | ST-P1-I  |       | ST-P2-I  |       | ST-P3-I  |       |
|---------|----------|-------|----------|-------|----------|-------|
| Sample  | $A_{gt}$ | $A_t$ | $A_{gt}$ | $A_t$ | $A_{gt}$ | $A_t$ |
| 1       | 20.8%    | 35.1% | 21.1%    | 34.6% | 14.2%    | -     |
| 2       | 20.1%    | 36.0% | 21.0%    | 35.0% | 17.4%    | 34.0% |
| 3       | 18.1%    | -     | -        | -     | -        | -     |
| Average | 19.7%    | 35.5% | 21.0%    | 34.8% | 15.8%    | 34.0% |
| St.dev  | 1.13%    | 0.44% | 0.05%    | 0.20% | 1.60%    | -     |
|         | ST-P1-T  |       | ST-P2-T  |       | ST-P3-T  |       |
| Sample  | $A_{gt}$ | $A_t$ | $A_{gt}$ | $A_t$ | $A_{gt}$ | $A_t$ |
| 1       | 17.0%    | -     | 17.7%    | 31.0% | 12.1%    | 25.6% |
| 2       | 18.8%    | 35.2% | 14.5%    | -     | 11.1%    | -     |
| 3       | 17.0%    | -     | -        | -     | -        | -     |
| Average | 17.6%    | 35.2% | 16.1%    | 31.0% | 11.6%    | 25.6% |
| St.dev  | 0.87%    | 0.00% | 1.63%    | -     | 0.48%    | -     |

## 2.2.2 Small punch tests

For Small Punch testing a sample can be removed either by drilling by a tube drill, which leaves a cylindrical sample of minimum 8 mm diameter, or by a larger tube drill applied in a small angle to the surface. Also in special cases, dedicated wire erosion methods can be applied. The Small Punch specimen size is just 8 mm in diameter with thickness of 0.5 mm. In practice, the sample should be at least 0.7 mm thick because it must be ground on both sides in order to remove any deformation produced by the sample removal process. The test specimens were prepared by a subcontractor by cutting 0.7 mm thick slices from which 8 mm diameter specimens were cut by wire erosion and ground on both sides to a thickness of  $0.500 \pm 0.005$  mm. All the specimens fulfilled the thickness requirement.

### Methods

Tensile Small Punch tests were carried out according to the prEN15627 [3] draft standard at room temperature at a puncher displacement rate of 0.3 mm/min. Load was measured by a calibrated load cell and the specimen deflection was measured from below by a digital displacement transducer. The schematic test arrangement is shown in Figure 4. From each test, a load-deflection curve is measured as shown in Figure 28. At room temperature, the deflection measurement rod (part D in Figure 4) does not have to have a thermocouple. That is necessary only in Small Punch creep testing at elevated temperatures where a direct measurement of the test specimen temperature is crucial.

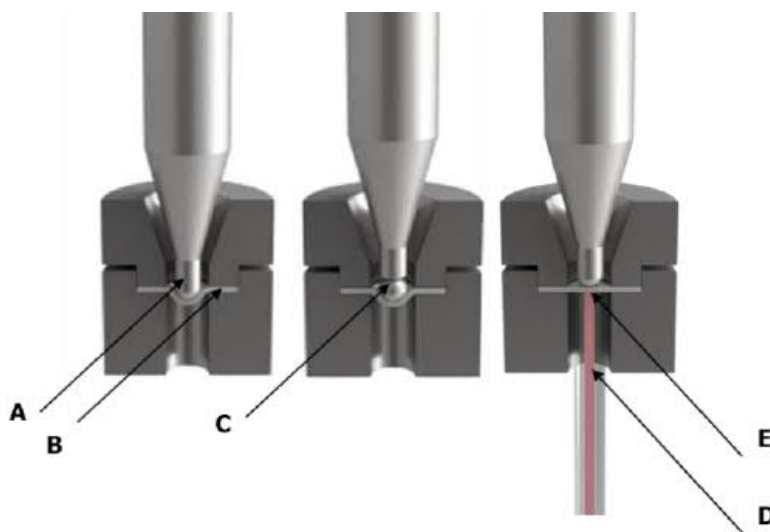


Figure 4. Small Punch test arrangement, where A is the punch; B is the specimen; C is the punch-ball; D is a ceramic rod for displacement measurement (and temperature E); E is the location where a thermocouple can be integrated into the ceramic displacement rod.

The calculation of yield strength is based on two lines between deflections 0 and 0.5 mm fitted by a dedicated bilinear method where the fitting error is minimised as shown in Figure 31. For calculation of the yield stress, the load at the intersection point is used (load  $F_e$  in Figure 31). The load-deflection curves are shown for ST-B1 in Figure 11 and for ST-B2 in Figure 12. In the fourth test for ST-B2, there was an operator error when the deflection measurement transducer was properly set up and therefore the deflection could not be recorded. Therefore the yield and ultimate tensile strength values for test no 4 are estimated on the basis of cross-head movement and comparison with test no 2 because for these two test the cross-head displacement curves were practically overlapping. The yield strength values were calculated according to the Equation (1) (D.1 in the prEN15627 [3] draft standard) with a coefficient value of 0.51:

$$R_{p0.2} = \beta_{Rp0.2} \cdot \frac{F_e}{h_0^2} \quad (1)$$

where  $F_e$  is the yield load measured as in Figure 31 and  $h_0$  is the specimen thickness. The ultimate tensile strength values were calculated according to the Equations (2) and (3) (C.1 and C.2 in the prEN15627 [3] draft standard) Equation (2) with a coefficient value of 0.2784 and Equation (3) with a coefficient value of 0.192.

$$R_m = \beta_{Rm} \cdot \frac{F_m}{h_0 u_m} \quad (2)$$

where  $F_m$  is the maximum load and  $u_m$  is the deflection at  $F_m$ .

$$R_m = \beta_{Rm} \cdot \frac{F_i}{h_0^2} \quad (3)$$

where  $F_i$  is the load at deflection  $u = 0.552$  mm. This equation is based on the idea that the active load carrying area is dependent on how far the ball has penetrated into the specimen.

## Results

The yield and ultimate tensile strength values are tabulated in Table 6. For *ST-B2* the yield strength value is higher than the ultimate tensile strength values, which is not physically possible. The ultimate strength values calculated by Equation (2) are systematically higher for *ST-B1*, but lower for *ST-B2* compared to the values calculated by Equation (3). The reason for this is the higher yield stress of *ST-B2* and therefore the different shape of the load-deflection curve is different and the  $F_i$  values are higher for *ST-B2*. The different load curve shape is seen clearly in Figure 30. In the case of the second sample *ST-B1*, the values for test 4 are based on cross-head movement and comparison with test 3.

The load curves can also be plotted as a function of stress as shown in Figure 32 and Figure 33 for *ST-B1*. It can be seen that the shape of the stress curves in Figure 32 and Figure 33 are rather similar and there is not much scatter between individual curves, but the maximum stress values are much lower when using Equation (3). The load-deflection curves from *ST-B2* are rather close to each other as seen in Figure 29. In addition, the stress curves in Figure 34 and Figure 35 are similar in shape, but the maximum stress is higher when using Equation (3).

The standard deviation for the yield strength in Table 6 is typically higher than for the tensile strength, and this was the case for *ST-B1*, but not for *ST-B2*, which showed exceptionally little scatter in the yield strength analysis. For *ST-B2* the yield strength value is higher than the ultimate tensile strength values, which is not physically possible, which shows that the current analysis method for yield strength is not very suitable for materials, which a yield strength close to the tensile strength. Then, the *ST-P1* specimen was tested by Small Punch method. For the assessment of tensile strength, the Equation (3) was used. The results for the web and flange are shown in Table 7. The agreement with the traditional test method is reasonable. The standard deviation for the flange material in SP testing was surprisingly low.

Table 6. Small punch test results

|         | ST-B1                          |                           |                           | ST-B2                          |                           |                           |
|---------|--------------------------------|---------------------------|---------------------------|--------------------------------|---------------------------|---------------------------|
| Sample  | $R_{p0.2}$<br>[MPa]<br>Eq. (1) | $R_m$<br>[MPa]<br>Eq. (2) | $R_m$<br>[MPa]<br>Eq. (3) | $R_{p0.2}$<br>[MPa]<br>Eq. (1) | $R_m$<br>[MPa]<br>Eq. (2) | $R_m$<br>[MPa]<br>Eq. (3) |
| 1       | 351                            | 584                       | 490                       | 679                            | 637                       | 656                       |
| 2       | 377                            | 585                       | 502                       | 680                            | 624                       | 643                       |
| 3       | 377                            | 577                       | 495                       | 691                            | 614                       | 639                       |
| 4       | 379                            | 573                       | 492                       | 677                            | 626                       | 645                       |
| Average | 371                            | 580                       | 495                       | 682                            | 626                       | 645                       |
| St.dev  | 13.4                           | 5.7                       | 5.3                       | 6.3                            | 9.5                       | 7.9                       |

Table 7. Small Punch test results for the web (ST-P1-I) and flange (ST-P1-W)

|         | ST-P1-I                        |                           | ST-P1-T                        |                           |
|---------|--------------------------------|---------------------------|--------------------------------|---------------------------|
| Sample  | $R_{p0.2}$<br>[MPa]<br>Eq. (1) | $R_m$<br>[MPa]<br>Eq. (2) | $R_{p0.2}$<br>[MPa]<br>Eq. (1) | $R_m$<br>[MPa]<br>Eq. (2) |
| 1       | 386                            | 498                       | 389                            | 481                       |
| 2       | 412                            | 500                       | 384                            | 486                       |
| 3       | 430                            | 492                       | 379                            | 491                       |
| Average | 409                            | 497                       | 384                            | 486                       |
| St.dev  | 22.1                           | 4.2                       | 5.0                            | 5.0                       |

### 2.2.3 Instrumented indentation testing

Instrumented indentation measurements were carried out to obtain material data to eventually extract the yield strength for the material. Anton Paar Tritec's UNHT device was used with a spherical ( $R=20\mu\text{m}$ ) indenter. The plan at start was to carry out similar measurements as described in [7]. However, this could not be carried out due to device limitations. The measurements were eventually carried out using several normal loads to obtain material information later on utilized in investigation of the yield strength of the material. A total of 10 repeated indentations were carried out per normal load using quadratic loading with loading and unloading time and hold time at the peak load of 15 seconds. The normal loads used varied between 1 and 75 mN. The measurements were carried out to ground and polished samples "2" (flange) (see Figure 5) and "4" (web) taken from a structural section *ST-P1*. The mean force-penetration graphs of indentations with normal loads 1-75 mN are shown in Figure 6 and Figure 7.

The data obtained from the nanoindentation includes e.g. elastic modulus ( $E$ ), hardness ( $H$ ) and stiffness ( $S$ ). Oliver & Pharr method [8] was utilized in the calculations. The plan was to use the nanoindentation data to draw a stress-strain curve and eventually calculate the material yield strength.

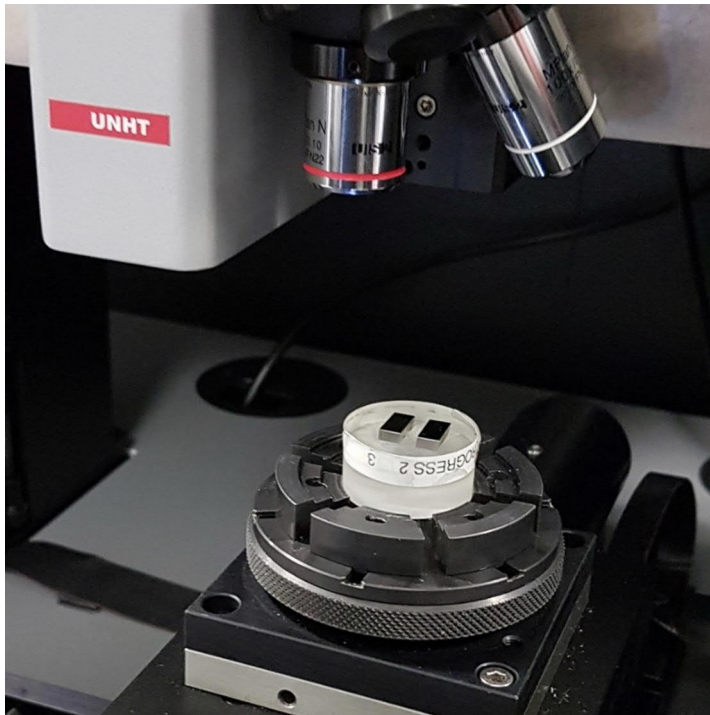


Figure 5. Sample "2" under the UNHT device.

Nanoindentation measurements were analyzed with the procedure described in [7]. An average value for the needed variables for each 10 repeated indentation loads were used to compute each stress and strain value. Young's modulus for the analysis EIT value was used. It takes into account the assumed Poisson's ratio (0.3 in this case) but it was found to be a bit low.  $E^*$  could have been more suitable as it was closer to the assumed value for these types of steels. The calculated young's moduli for the flange and web were 169 GPa and 168 GPa respectively. The effect of low young's modulus value to the stress-strain curve is assumed to be small. The plastic constrain factor was assumed to be 3 (as in [7]) which might be a bit low in our case since it has great impact on the calculated stress and a bit higher factor would have yielded more realistic values for the stress-strain curve. The stress-strain curves for both materials are presented in Figure 8 and Figure 9.

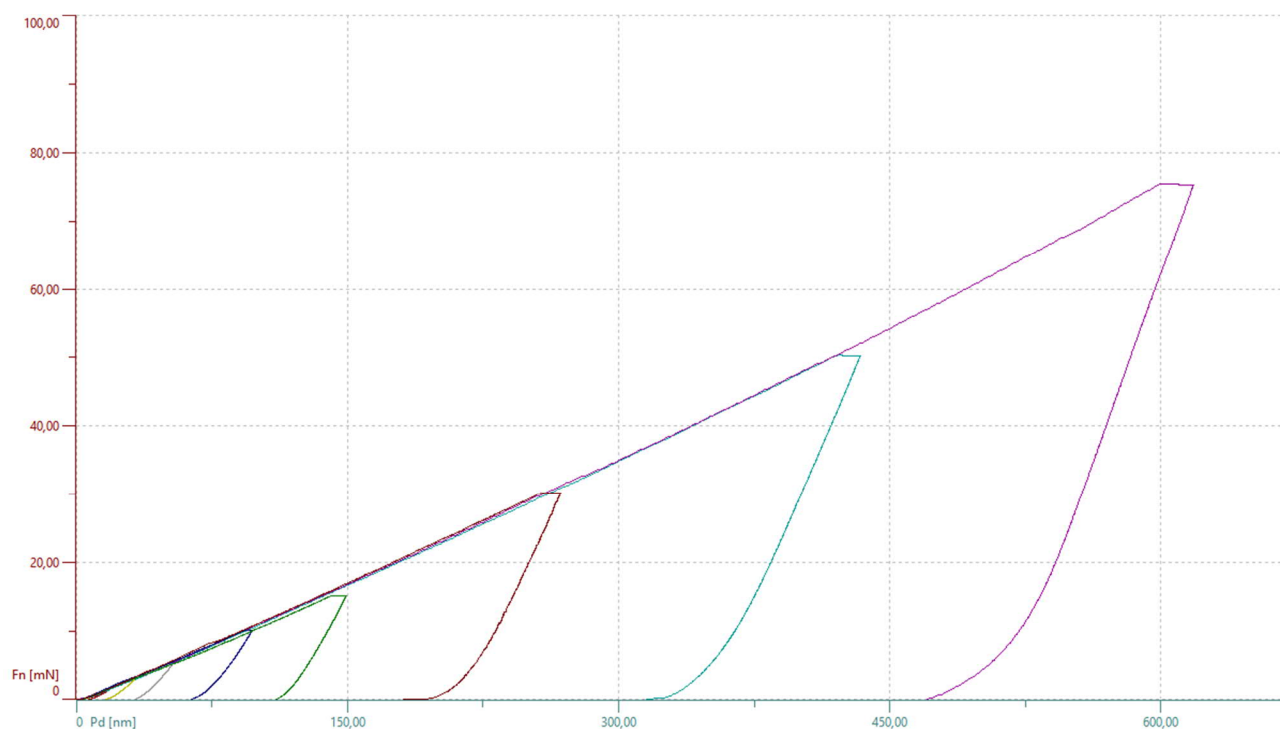


Figure 6. Mean force-penetration graphs of indentations with loads 1-75mN carried out on sample "2" (flange).

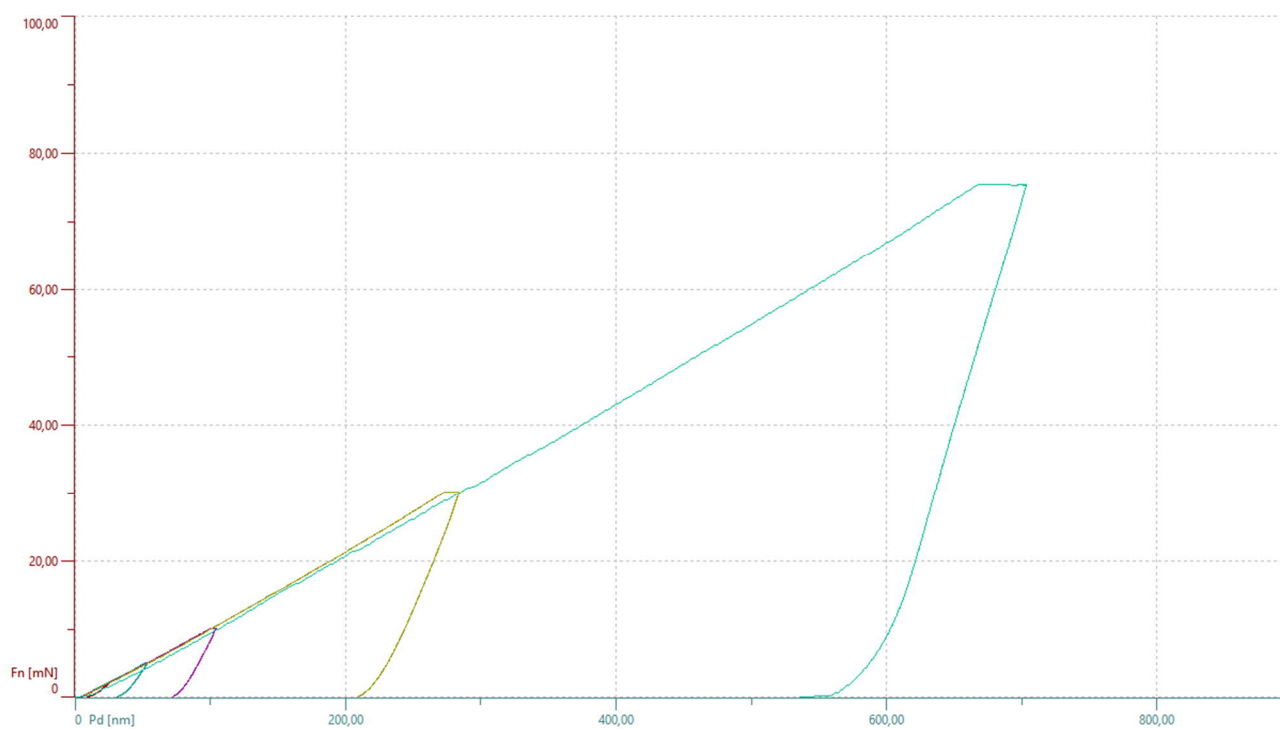


Figure 7. Mean force-penetration graphs of indentations with loads 2-75mN carried out on sample "4" (web).

The yield strength of the samples was found to be unrealistically high when the analysis procedure described in [7] was applied to analyze the stress-strain values on the basis of the individual indentations. The yield point when assumed to be the intersection point of the line with  $E^*$  as the slope and curve produced by the stress-strain point calculated from the indentations are found to be between 700 and 800 MPa in both cases when estimated from the Figure 8 and Figure 9. It seems that the procedure need deeper analysis to yield more realistic tensile strength values. Next step would be to analyze the indentation marks more deeply especially the area under the indentation whether there is any sign of sink-in or pile-up that have an impact to the area under the indentation and thus the stress values calculated from the depth-penetration curves.

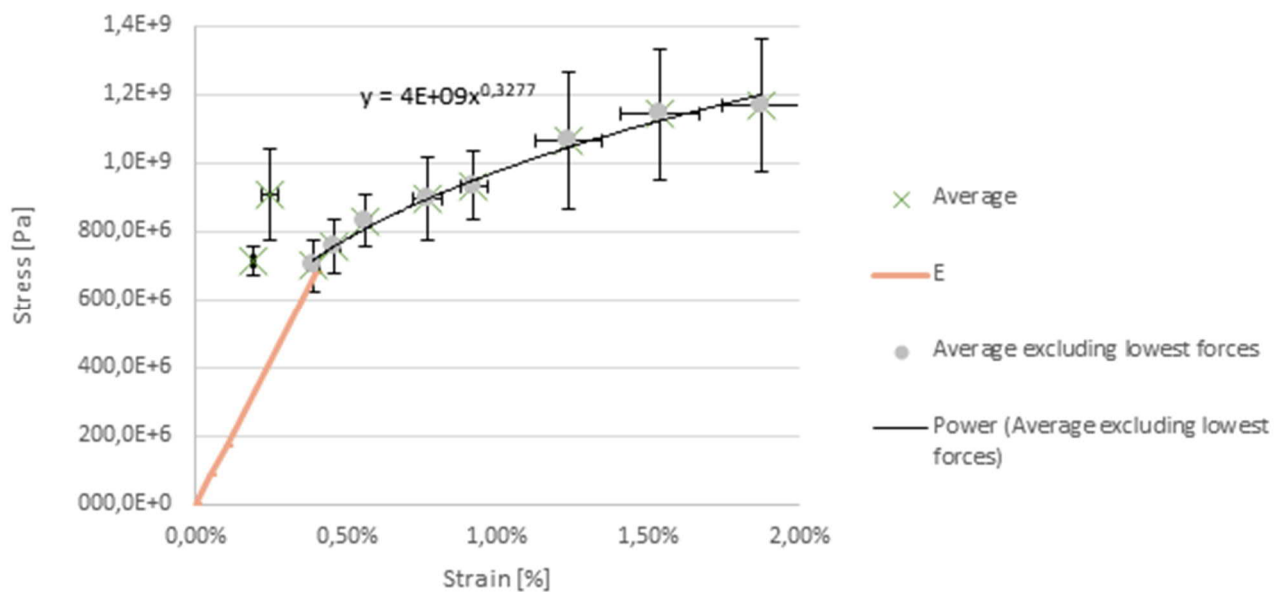


Figure 8. The approximated stress-strain curve for sample "2" (flange).

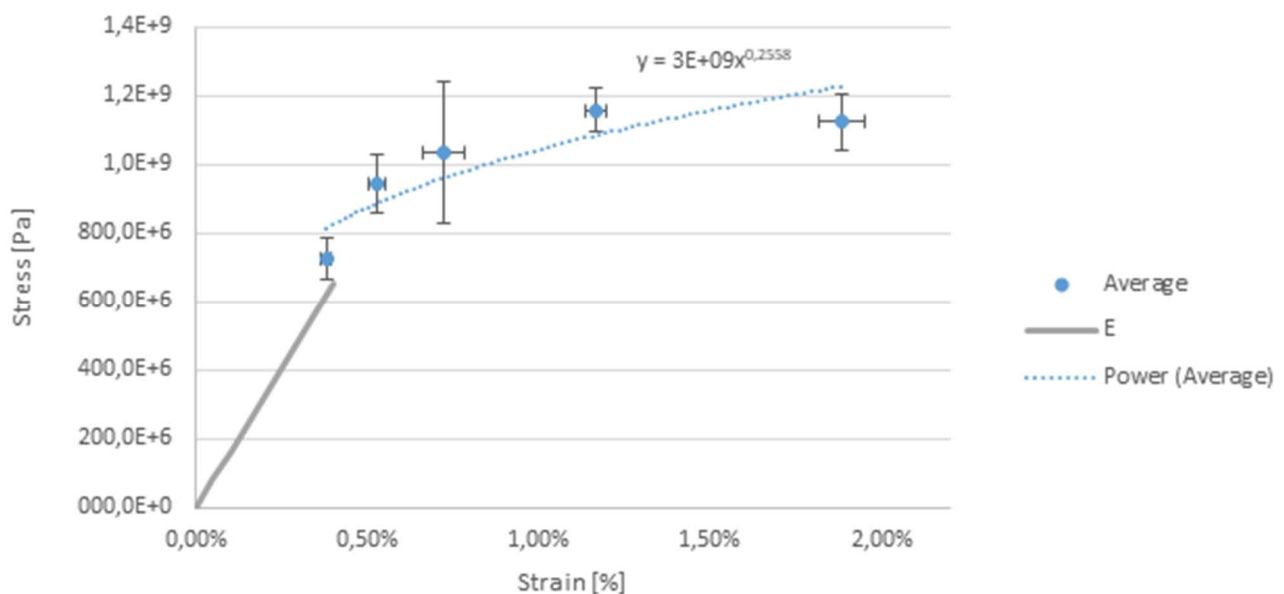


Figure 9. The approximated stress-strain curve for sample "4" (web).

#### 2.2.4 Sub-sized impact toughness testing

Sub-size Charpy specimens 5 x 5 x 27 mm were extracted from the web and the flange of hot-rolled section *ST-P1*, two specimens from each. The impact energies at room temperature were then converted to full size (10 x 10 x 55 mm) Charpy impact energy equivalents according to Equations 7.26 and 7.27 from [4]. The results are summarised in Table 8

*Table 8. Sub-size impact energies and their full size equivalents*

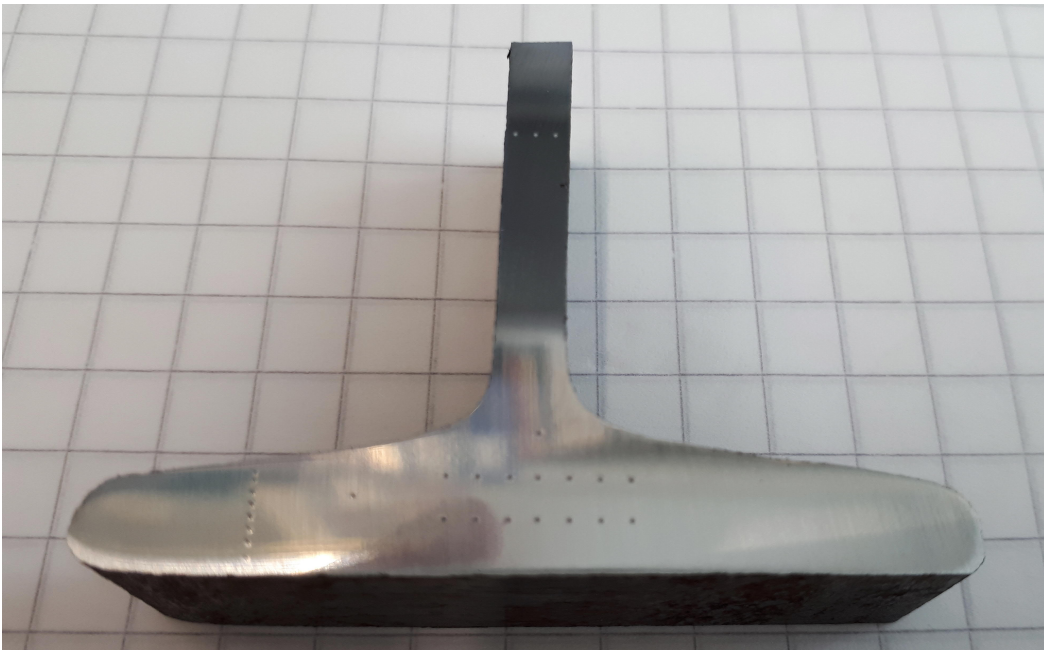
|                | ST-P1-I              |                         | ST-P1-T              |                         |
|----------------|----------------------|-------------------------|----------------------|-------------------------|
| Sample         | Impact energy<br>[J] | Full size equiv.<br>[J] | Impact energy<br>[J] | Full size equiv.<br>[J] |
| <b>1</b>       | 18.47                | 129                     | 14.02                | 91                      |
| <b>2</b>       | 17.45                | 121                     | 13.29                | 84                      |
| <b>Average</b> | <b>17.96</b>         | <b>125</b>              | <b>13.66</b>         | <b>88</b>               |
| <b>St.dev</b>  | <b>0.510</b>         | <b>4.0</b>              | <b>0.365</b>         | <b>3.5</b>              |

#### 2.2.5 Hardness testing

HV10 hardness measurements were conducted on the cross-section of the T-profile across the web and the flange and in the region of the intersection (see Figure 10). The hardness values were then converted to ultimate tensile strength equivalents according to EN ISO 18265 [5]. The results are summarised in Table 9.

*Table 9. Hardness (HV10) test results and the ultimate tensile strength equivalents from cross-section web (ST-P1-I), flange (ST-P1-T) and their intersection (ST-P1-X).*

|                | ST-P1-I    |                       | ST-P1-T    |                       | ST-P1-X    |                       |
|----------------|------------|-----------------------|------------|-----------------------|------------|-----------------------|
| Sample         | HV10       | $R_m$ equiv.<br>[MPa] | HV10       | $R_m$ equiv.<br>[MPa] | HV10       | $R_m$ equiv.<br>[MPa] |
| <b>Average</b> | <b>179</b> | <b>572</b>            | <b>154</b> | <b>492</b>            | <b>157</b> | <b>499</b>            |
| <b>St.dev</b>  | <b>3.6</b> |                       | <b>2.6</b> |                       | <b>6.3</b> |                       |



*Figure 10 Points of hardness measurements*

### **2.2.6 Summary of mechanical testing**

The experiments conducted on the structural steel elements didn't indicate any significant degradation of the material properties in the extracted materials from ST-P1 to ST-P3 sections and the material quality seems to be the same as in the time of the fabrication of the steelwork that was tested. It can be concluded that structural steel section ST-P1 would qualify as S355JR grade. However, the tensile strength of the structural angle ST-C was slightly below the minimum value of USt 37-1 according to DIN EN 17100. Whether this can be accounted to the ageing of the material or some other effect could not be confirmed.

Two new methods for minimum-invasive experimental verification of steel tensile properties were tested. Small punch testing provided good prediction of the tensile strength and very small standard deviation of the results, but this method is not fully portable and needs specimens to be sent to the laboratory. It was more difficult to predict accurately the yield strength of work-hardened steel (ST-B2) On the other hand, prediction of the tensile strength by instrumented indentation was not very successful as this method needs more development for the conversion of measured results to the stress-strain relationship. The method can be potentially fully portable and more accurate than on-site hardness measurements.

The comparison of the prediction of yield and ultimate strength of the material is in Figure 11 and Figure 12 for bars ST-B1 and ST-B2 and in Figure 13 and Figure 14 for structural section ST-P1.

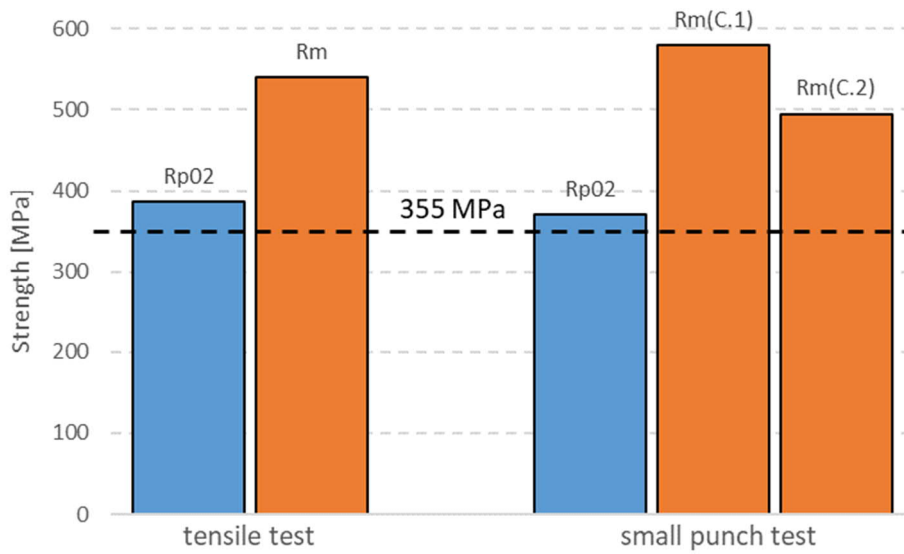


Figure 11 Comparison of mechanical test results of 24 mm stud ST-B1

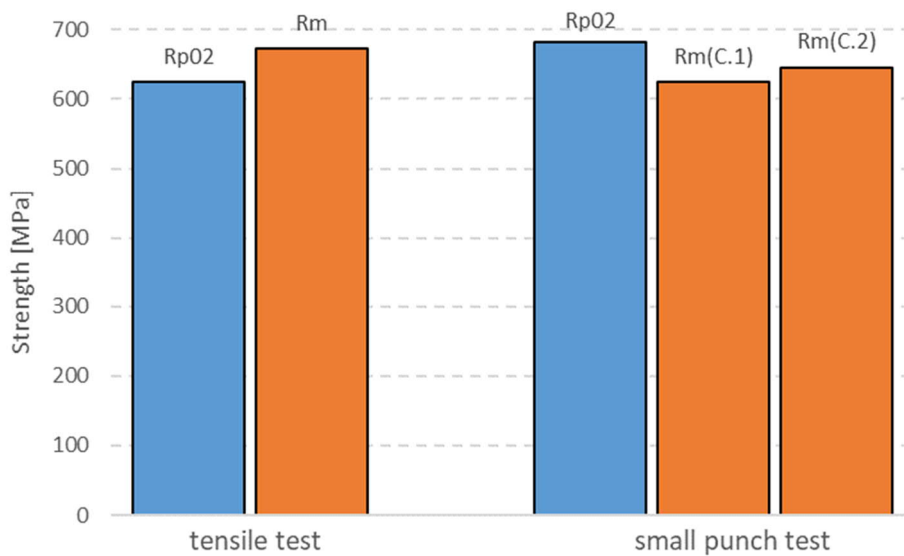


Figure 12 Comparison of the test results of 18 mm tie ST-B2

From the initial testing of Small Punch method on steel bars, it can be seen that the calculation of tensile strength according to method C.2 (Equation (3)) is more accurate, and therefore this method was used in the further tests on the structural profiles recovered from the single-storey steel hall.

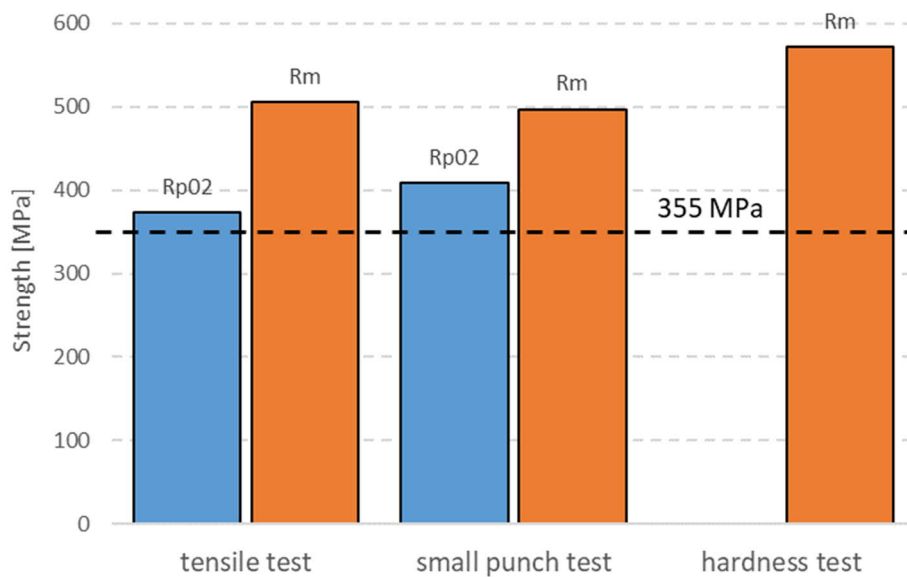


Figure 13 Comparison of the test results of I-section ST-P1-I (web)

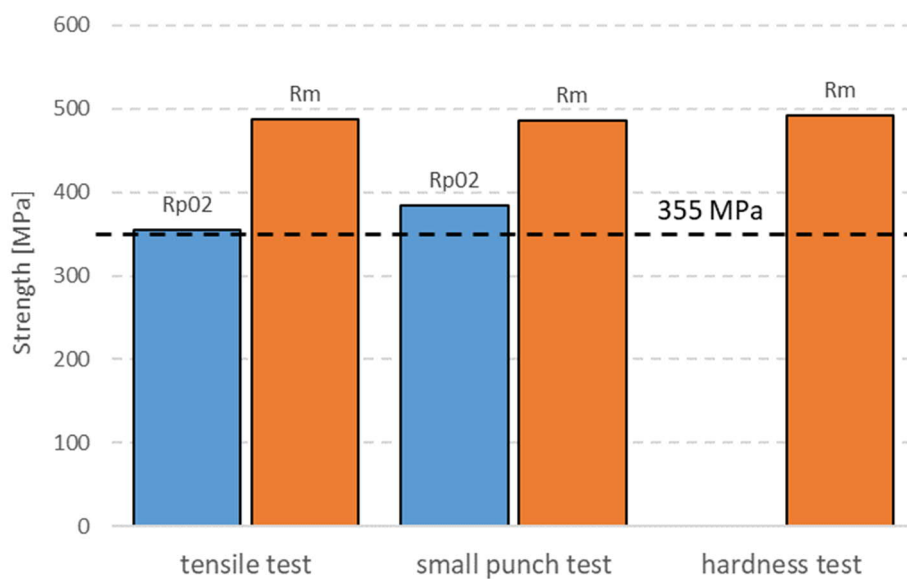


Figure 14 Comparison of the test results of I-section ST-P1-T (flange)

## 2.3 Testing of chemical properties

The chemical composition of the sample extracted from the structural angle ST-C was verified and the results expressed as element's mass fraction are presented in Table 10. Then the macrographic examination by sulphur print (Baumann method) was conducted on the cross-section (see Figure 15). The results were compared with the limits specified in DIN 17100 [6] for the steel U St37-1. St37 is a basic unalloyed low-carbon steel grade with the tensile strength 370 MPa.

*Table 10. Chemical testing results of sample ST-C*

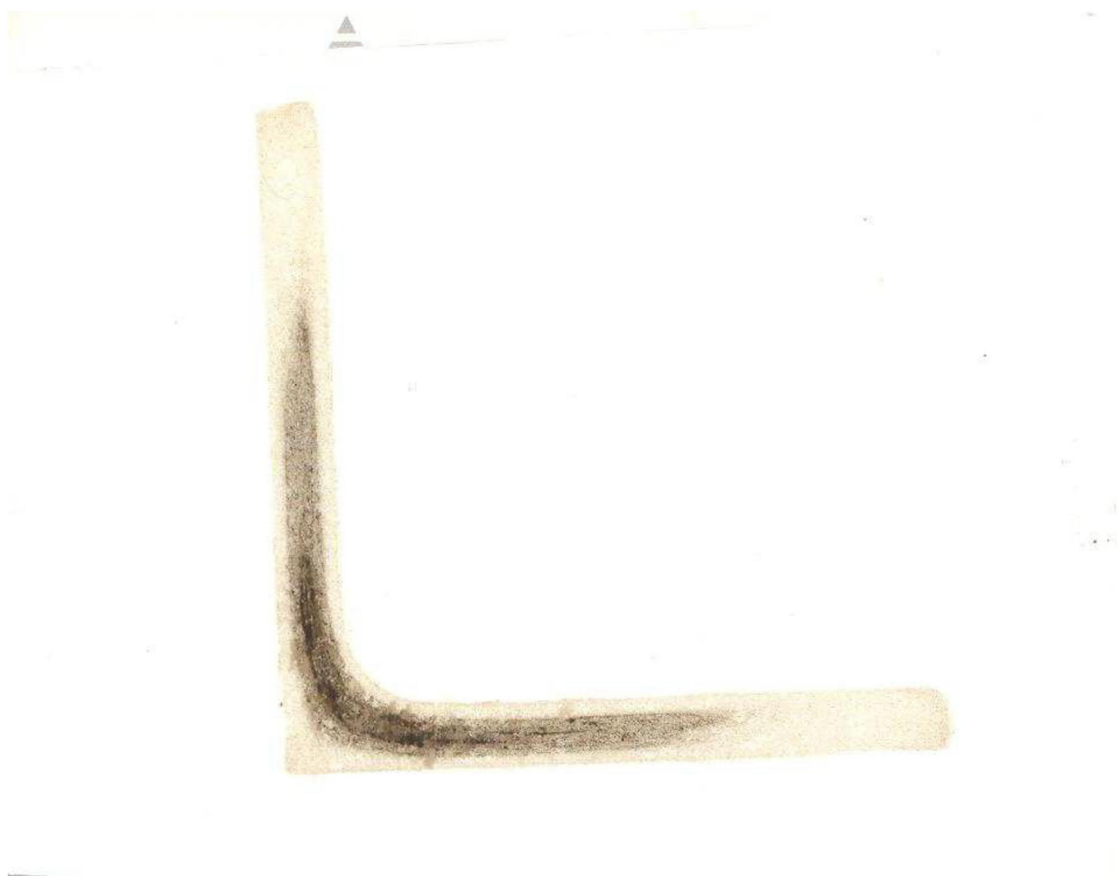
| Element | Mass fraction [%]    | Specification of USt37-1 according to DIN 17100 |
|---------|----------------------|-------------------------------------------------|
| C       | 0.034                | max. 0.25                                       |
| Si      | <0.01                | -                                               |
| Mn      | 0.29                 | -                                               |
| P       | 0.067 <sup>1</sup>   | max. 0.090                                      |
| S       | 0.070 <sup>2</sup>   | max. 0.063                                      |
| Cr      | <0.01                | -                                               |
| Mo      | <0.01                | -                                               |
| Ni      | 0.03                 | -                                               |
| Al      | <0.001               | -                                               |
| Cu      | 0.04                 | -                                               |
| Nb      | <0.002               | -                                               |
| Ti      | <0.002               | -                                               |
| V       | <0.002               | -                                               |
| N       | 0.02143 <sup>3</sup> | -                                               |

<sup>1</sup> Maximum value ~0.109%

<sup>2</sup> Maximum value ~0.102%

<sup>3</sup> Maximum value ~0.0273%

As can be seen from Table 10, several elements were higher than the limits for the mild steel U St37-1 according to DIN 17100 [6], but the macrographic examination on Figure 15 did not reveal any defects, porosity, cracks or other irregularities in the cross-section. Such profile has to be excluded from welding, but if the mechanical properties are satisfactory, it might be able to carry the mechanical load. It would be impossible to obtain CE marking for this material, as there is no harmonized standard or ETA approval to which the performance can be declared.



*Figure 15 Sulphur print for the macrographic examination*

### 3 Verification of the quality of the envelope

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#### 3.1 Test specimens

##### 3.1.1 Mineral wool (MW) panels

Mineral-wool sandwich panel tests for used panels were carried out in Finland in 2018. The tested panels were dismantled from experimental building (See Figure 3-1) located in Hämeenlinna, Finland. The building was used for experimental research for long-term behaviour of sandwich panels during 2000-2007. After the research, the building was equipped with new vertical installed 150 mm thick and 1200 mm width mineral-wool sandwich panels in 2007. In that time also 0-series structural factory tests according to EN14509 standards were conducted to the same batch of panels as installed. Thus, there are available reference values to the 2018 tested values and the ageing behaviour of the panels was possible to evaluate. Further to structural testing, also lambda-tests for core material and coating tests for external steel sheet were made. Removed panels were in southern and northern façade. The lengths of the panels were 3,8 m and 5,1 m. Three whole width (1200 mm) panels were in both facades. Furthermore some longitudinally cut panels were also utilized for small sample tests. Figure 16 shows southern façade of the building where the panels were removed.



*Figure 16 Test building from where sandwich panels were dismantled (South façade)*

### ***Dismounting process***

The dismounting process started with marking of the panels, planning of dismounting order and preparing transporting packages. The dismounting was realised in 25<sup>th</sup> to 26<sup>th</sup> of June 2018. Temperature was about 18 to 24°C and weather was half-cloudy without raining during the dismounting. First, all flashings were removed carefully and panels were visually inspected. Figure 17 shows preparation of dismounting. The panels were one span panels screwed only in the ends with three screws per end. The panels were extracted from the building frame and lifted with crane with help of panel lifting device carefully onto a timber forklift pallet. The dismounting went smoothly without damages to the panels (see Figure 18). The packages were well protected for transportation and transported into the panel factory in Alajärvi, Finland. Panel marking and numbering is shown in Figure 19.



*Figure 17 Preparing dismounting*



*Figure 18 Dismounting of panels with crane.*

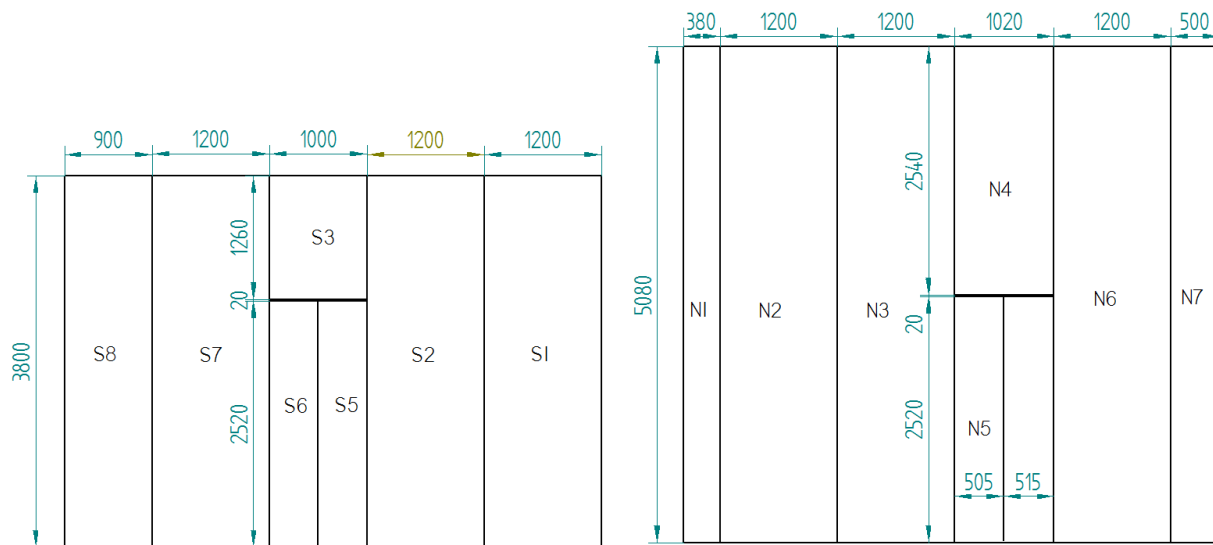


Figure 19 Panel marking from outside (S=South, N=North). Panel N4 is from different production patch.

### 3.1.2 Polyurethane (PIR) panels

In 2005 the research building Sandwich-Demo-House was built by the Institute of Steel and Lightweight Metal Construction of RWTH Aachen University in cooperation with the International Federation for Lightweight Metal Construction (IFBS) in Aachen. The aim of this project was to test various aspects of lightweight metal construction under real boundary conditions. Various building physics investigations were carried out in the sandwich demo house. Furthermore the use of different sandwich manufacturers and the different laying of the sandwich elements led to further empirical values in the construction method. Figure 20 shows the Sandwich-Demo-House.



Figure 20 Sandwich-Demo-House

The research building was built in lightweight metal construction. For each wall a different sandwich manufacturer was chosen as already described. The wall elements have a micro-profiled outer shell and a lined inner shell. The outer shells of all elements are 0.6 mm thick and the inner shells are 0.5 mm thick. The south and west walls were installed horizontally, and the north and east walls were installed vertically. Seven sandwich elements were used on each side. A different colour was chosen for each of the four walls to investigate their influence on the properties of the walls. The sandwich

elements on the north side are blue, those on the east side are green, the south side is yellow, and the west side is red.

As part of the project, the south and west walls were dismantled and then tested for their mechanical properties in accordance with EN 14509 [9]. This allows a comparison to be made with the target values of the WPK tests from the approvals and the evaluation of reuse. Thereby, the following values were determined:

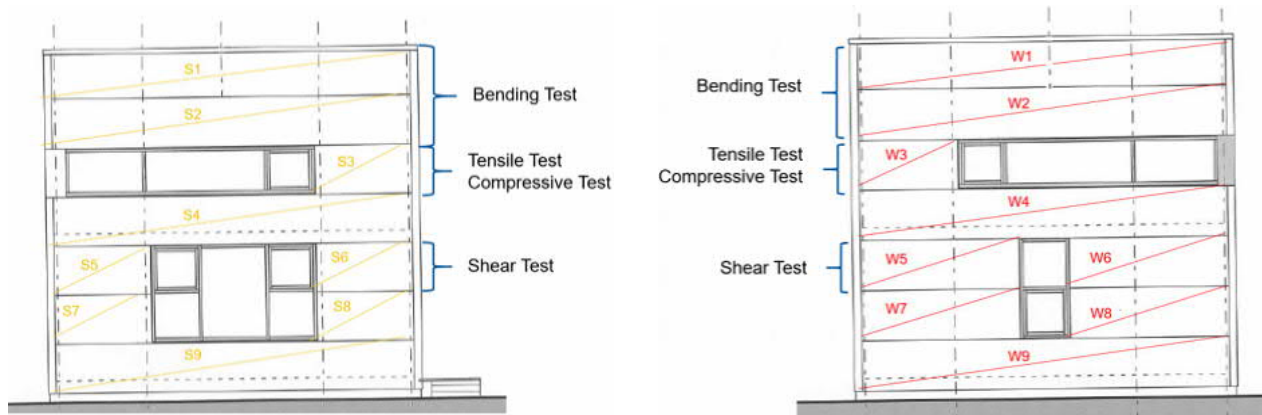
- Tensile Strength- and Tensile Modulus
- Compressive Strength and Compressive Modulus
- Shear Strength and Shear Modulus
- Wrinkling Stress

Figure 20 shows the dismantling process of the south- and westside of the Sandwich-Demo-House.



*Figure 21 Dismantling Process of Sandwich-Demo-House*

The following illustration shows the designation and position of the panels that were used for the tests. For both walls, only the upper elements could be used for the bending tests, as only these had the necessary length and no window recesses.



*Figure 22 Designation and Position of the Panels used for testing*

### 3.1.3 One-sided fasteners

The following fasteners illustrated in Figure 23 were used in the test series:

- SL2-T-A14-4.8x20 (self-drilling screw) (marked as 'SL2')
- SL3-H15-6.3x32 (self-drilling screw) (marked as 'SL3')
- SL3-H15-S16-6.3x32 (self-drilling screw) (marked as 'SL3-S16')

Self-drilling screws were manufactured by SFS Intec.

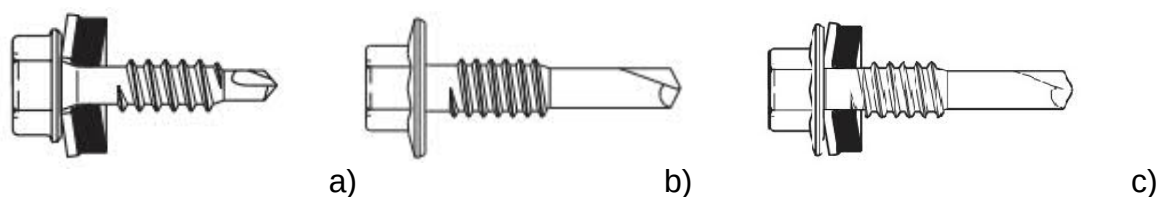


Figure 23 Fasteners studied in the tests: a) SL2-T-A14-4.8x20, b) SL3-H15-6.3x32, c) SL3-H15-S16-6.3x32

The following sheet steels were fixed with the studied fasteners to the exterior faces of sandwich panels:

- S280GD + Z275 PE; nominal thickness 0.6 mm (marked as "S280 t=0.6 mm")
- S350; nominal thickness 1.0 mm (marked as "S350 t=1.0 mm")

Sandwich panel 150R50 pieces were tested. The nominal thickness of the steel surface was 0,6 mm. Test samples were cut from different panels: 5 tensile and 5 shear test samples were cut from the sandwich panel which was facing north (marked as "N4", "N5") and same number of samples was cut from the sandwich panel which was facing south (marked as "S1", "S3"). In shear tests the nominal size of the test specimen was 400 mm × 200 mm × 150 mm and in the tensile tests 400 mm × 400 mm × 150 mm. Test combinations and number of tests are presented in Table 3-11 Tested panel side, fasteners, fixed sheet metals and number of tests according to the loading type studied in the test programme Table 11.

Table 11 Tested panel side, fasteners, fixed sheet metals and number of tests according to the loading type studied in the test programme

| Test    | Panel | Fastener | Sheet metal fixed to the face | Number |
|---------|-------|----------|-------------------------------|--------|
| Shear   | N4    | SL3      | S350 (t=1.0 mm)               | 5      |
|         | S3    | SL3      |                               | 3      |
| Tensile | N5    | SL2      | S280 (t=0.6 mm)               | 1      |
|         | N4    | SL3      | S350 (t=1.0 mm)               | 1      |
|         |       |          |                               | 3      |
|         | S1    | SL2      | S280 (t=0.6 mm)               | 2      |
|         |       | SL3      | S350 (t=1.0 mm)               | 3      |

## 3.2 Structural tests

Structural tests of MW panels were carried out at Alajärvi panel factory in Finland, PIR panels were tested in RWTH Aachen in Germany.

Structural testing included following measurements and tests according to EN 14509 [9]:

- Density of the core material
- Compressive strength and modulus of elasticity of core material
- Cross panel tensile test
- Vacuum chamber tests for whole panel (bending or shear strength)

Because the limited number of MW specimen and actual lengths, separate bending and shear tests were not able to carry out, but only vacuum chamber tests were made and failure mode was depended on the panel dimensions. Material properties for the panels as follows:

- External facing: S320GD+Z /0.6 mm, polyester or PVDF\* coating, colour dark grey RR23
- Internal facing: S320GD+Z /0.6 mm, polyester coating, colour white RR20
- Core: constructive stone wool lamella-core; CES50CS100 (Paroc Oy Ab)

\*Panel N:o N4

### 3.2.1 Density of the core material

Measured densities of mineral wool pieces are shown in Table 12. Both results from 2007 and 2018 measurements are presented. Nominal density of Paroc CES50CS100 MW-grade is 115 kg/m<sup>3</sup>. An average value for original panels was 124.8 kg/m<sup>3</sup> whereas for demounted panels it was 115.8 kg/m<sup>3</sup>. Difference is about 7%. There is no remarkable difference between north and south façade panels.

Table 12 Measured densities of mineral wool [kg/m<sup>3</sup>]

| Year    | 2007   | 2018  |       |       |       |       |       |       |        |       |       |
|---------|--------|-------|-------|-------|-------|-------|-------|-------|--------|-------|-------|
| Sample  | MW Ref | MW S1 | MW S2 | MW S3 | MW S6 | MW S7 | MW S8 | MW N3 | MW N4* | MW N5 | MW N6 |
| 1       | 122.5  | 114.0 | 114.0 | 112.0 | 124.0 | 118.0 | 113.0 | 115.0 | 118.0  | 115.0 | 116.0 |
| 2       | 121.0  | 118.0 | 116.0 | 117.0 | 114.0 | 112.0 | 112.0 | 116.0 | 116.0  | 117.0 | 116.0 |
| 3       | 122.0  | 114.0 | 115.0 | 120.0 | 119.0 | 116.0 | 112.0 | 117.0 | 112.0  | 115.0 | 114.0 |
| 4       | 130.5  | 112.0 | 111.0 | 114.0 | 119.0 | 120.0 | 113.0 | 116.0 | 116.0  | 117.0 | 118.0 |
| 5       | 125.5  | 114.0 | 115.0 | 115.0 | 119.0 | 116.0 | 113.0 | 116.0 | 122.0  | 118.0 | 117.0 |
| 6       | 127.5  | 115.0 | 116.0 | 118.0 | 120.0 | 116.0 | 112.0 | 118.0 | 120.0  | 117.0 | 117.0 |
| Average | 124.8  | 114.5 | 114.5 | 116.0 | 119.2 | 116.3 | 112.5 | 116.3 | 117.3  | 116.5 | 116.3 |

\*Not included to analyses

### 3.2.2 Compression tests

The compressive test is used to determine the compressive strength and modulus of the panel core. The compressive strength  $f_{Cc}$  and the modulus  $E_{Cc}$  are calculated according to equation (1).

$$f_{Cc} = \frac{F_{10\%}}{A} \text{ and } E_{Cc} = \frac{\Delta F d_c}{\Delta w A} \quad (1)$$

where  $F_{10\%}$  is applied force at 10 % compression,  $A$  is cross section of the specimen,  $\frac{\Delta F}{\Delta w}$  is the slope of the linear part of the force-compression curve,  $d_c$  is thickness of the panel.

The PIR panel specimens were placed between two stiff steel plates. The deflection rate was defined with 2 mm/min. The specimen was loaded up to a compression of 10%. A load-compression curve and the applied force  $F_{10\%}$  were recorded. MW specimen dimensions are 124 x 124 mm. Measured values of compression strength are shown in Table 13 and in more detail in Annex B.

Table 13 Measured values for compression strength of mineral wool [MPa]

| Year           | 2007         | 2018         |              |              |              |              |              |              | 2020         |              |
|----------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Sample         | MW Ref       | MW S1        | MW S3        | MW S6        | MW S7        | MW S8        | MW N4*       | MW N5        | PIR S3       | PIR W3       |
| 1              | 0.117        | 0.116        | 0.104        | 0.112        | 0.124        | 0.101        | 0.124        | 0.098        | 0.125        | 0.165        |
| 2              | 0.125        | 0.108        | 0.111        | 0.119        | 0.127        | 0.121        | 0.123        | 0.103        | 0.117        | 0.159        |
| 3              | 0.152        | 0.105        | 0.107        | 0.101        | 0.120        | 0.124        | 0.118        | 0.127        | 0.131        | 0.163        |
| 4              | 0.144        | 0.103        | 0.116        | 0.131        | 0.123        | 0.116        | 0.111        | 0.097        | 0.129        | 0.164        |
| 5              | 0.101        | 0.113        | 0.114        | 0.100        | 0.111        | 0.120        | 0.112        | 0.087        | 0.140        | 0.162        |
| 6              | 0.102        | -            | -            | -            | -            | -            | -            | -            | -            | -            |
| 7              | 0.100        | -            | -            | -            | -            | -            | -            | -            | -            | -            |
| 8              | 0.098        | -            | -            | -            | -            | -            | -            | -            | -            | -            |
| 9              | 0.118        | -            | -            | -            | -            | -            | -            | -            | -            | -            |
| 10             | 0.123        | -            | -            | -            | -            | -            | -            | -            | -            | -            |
| <b>Average</b> | <b>0.118</b> | <b>0.109</b> | <b>0.111</b> | <b>0.112</b> | <b>0.121</b> | <b>0.117</b> | <b>0.117</b> | <b>0.102</b> | <b>0.128</b> | <b>0.163</b> |
| <b>St.dev</b>  | <b>0.019</b> | <b>0.005</b> | <b>0.005</b> | <b>0.013</b> | <b>0.006</b> | <b>0.009</b> | <b>0.006</b> | <b>0.015</b> |              |              |

\*Not included to analyses

Mean value of all MW tested values in 2018 was 0.112 N/mm<sup>2</sup> whereas standard deviation was 0.011 N/mm<sup>2</sup>. It can be concluded that compression strength was only 5% lower than the original one from 2007. The declared 5% fractile of PIR panels compression strength 0.100 MPa is lower than the 5% fractile of the measured strength 0.109 and 0.157 MPa for south and west panels respectively.

Measured elastic moduli in compression tests are shown in Table 14 and in more detail in Annex B.

*Table 14 Measured values for elastic moduli in compression tests [MPa]*

| Year           | 2007      | 2018     |          |          |          |          |           |          | 2020      |           |
|----------------|-----------|----------|----------|----------|----------|----------|-----------|----------|-----------|-----------|
| Sample         | MW<br>Ref | MW<br>S1 | MW<br>S3 | MW<br>S6 | MW<br>S7 | MW<br>S8 | MW<br>N4* | MW<br>N5 | PIR<br>S3 | PIR<br>W3 |
| 1              | 7.0       | 10.1     | 5.9      | 4.4      | 11.8     | 8.3      | 11.1      | 5.5      | 3.01      | 3.66      |
| 2              | 7.0       | 10.3     | 7.8      | 10.2     | 10.1     | 10.1     | 6.3       | 8.5      | 3.00      | 3.75      |
| 3              | 11.0      | 11.0     | 5.2      | 6.7      | 8.4      | 11.0     | 6.9       | 5.2      | 3.07      | 3.58      |
| 4              | 9.0       | 11.5     | 5.8      | 11.5     | 13.4     | 9.8      | 9.8       | 4.0      | 3.20      | 3.59      |
| 5              | 8.0       | 13.0     | 7.6      | 10.0     | 9.6      | 10.7     | 6.6       | 6.9      | 3.15      | 3.77      |
| 6              | 6.0       | -        | -        | -        | -        | -        | -         | -        | -         | -         |
| 7              | 6.0       | -        | -        | -        | -        | -        | -         | -        | -         | -         |
| 8              | 6.0       | -        | -        | -        | -        | -        | -         | -        | -         | -         |
| 9              | 12.0      | -        | -        | -        | -        | -        | -         | -        | -         | -         |
| 10             | 7.0       | -        | -        | -        | -        | -        | -         | -        | -         | -         |
| <b>Average</b> | 7.9       | 11.2     | 6.5      | 8.5      | 10.6     | 10.0     | 8.1       | 6.0      | 3.09      | 3.67      |
| <b>St.dev</b>  | 2.1       | 1.2      | 1.1      | 2.9      | 2.0      | 1.1      | 2.2       | 1.7      |           |           |

\*Not included to analyses

Average value of all MW tests from 2018 is 8.8 N/mm<sup>2</sup> that is bit higher than the 2007 result. Declared 5% fractile of modulus of elasticity of the west PIR panel 2.5 MPa is lower than the 5% fractile of the tests 3.46 MPa. However, the declared values for south PIR panels 2.93 MPa and 3.57 MPa for 5% fractile and average modulus of elasticity respectively are higher than the measurements.

### 3.2.3 Tensile tests

In this test series, the tensile strength  $f_{ct}$  and the tensile modulus  $E_{ct}$  will be determined. The tensile strength  $f_{ct}$  and the tensile modulus  $E_{ct}$  is calculated according to equation (2). Thereby, it is necessary to say, that the standard EN 14509 [9] allows a decrease of the tensile test  $f_{ct}$  of 50 % during the ageing process.

$$f_{ct} = \frac{F_u}{A} \text{ and } E_{ct} = \frac{\Delta F d_c}{\Delta w A} \quad (2)$$

Where  $F_u$  is maximum tensile load,  $A$  is cross section of the specimen,  $\frac{\Delta F}{\Delta w}$  is the slope of the linear part of the force-displacement curve and  $d_c$  is thickness of the panel. It should be noted that the standard EN 14509 [9] allows a decrease of the tensile test  $f_{ct}$  of 50% during the ageing process.

Samples were taken from the sandwich panels and tested in a tensile testing machine. The PIR specimens have dimensions of 150 x 150 mm and are 100 mm thick, MW specimens have dimension 124 x 124 mm. Measured values of tensile strength are shown in Table 15, elastic modules in tensile tests are shown in Table 16 and in more detail in Annex B.

Table 15 Measured values for tensile strength [MPa]

| Year    | 2007   | 2018  |       |       |       |       |        |       | 2020   |        |
|---------|--------|-------|-------|-------|-------|-------|--------|-------|--------|--------|
| Sample  | MW Ref | MW S1 | MW S3 | MW S6 | MW S7 | MW S8 | MW N4* | MW N5 | PIR S3 | PIR W3 |
| 1       | 0.072  | 0.112 | 0.103 | 0.021 | 0.113 | 0.111 | 0.060  | 0.083 | 0.078  | 0.071  |
| 2       | 0.071  | 0.098 | 0.102 | 0.082 | 0.105 | 0.097 | 0.090  | 0.109 | -      | 0.076  |
| 3       | 0.046  | 0.113 | 0.083 | 0.088 | 0.127 | 0.068 | 0.058  | 0.113 | -      | -      |
| 4       | 0.049  | 0.073 | 0.055 | 0.088 | 0.109 | 0.057 | 0.049  | 0.114 | -      | -      |
| 5       | 0.060  | 0.117 | 0.092 | 0.084 | 0.078 | 0.068 | 0.110  | 0.094 | 0.076  | 0.101  |
| 6       | 0.040  | -     | -     | -     | -     | -     | -      | -     | 0.064  | 0.077  |
| 7       | 0.044  | -     | -     | -     | -     | -     | -      | -     | 0.059  | 0.078  |
| 8       | 0.093  | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| 9       | 0.034  | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| 10      | 0.052  | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| Average | 0.056  | 0.103 | 0.087 | 0.073 | 0.106 | 0.080 | 0.074  | 0.102 | 0.069  | 0.080  |
| St.dev  | 0.018  | 0.018 | 0.020 | 0.029 | 0.018 | 0.023 | 0.026  | 0.013 |        |        |

\*Not included to analyses

Table 16 Measured values for elastic moduli in tensile tests [MPa]

| Year    | 2007   | 2018  |       |       |       |       |        |       | 2020   |        |
|---------|--------|-------|-------|-------|-------|-------|--------|-------|--------|--------|
| Sample  | MW Ref | MW S1 | MW S3 | MW S6 | MW S7 | MW S8 | MW N4* | MW N5 | PIR S3 | PIR W3 |
| 1       | 13.0   | 8.3   | 15.5  | 11.7  | 11.0  | 5.4   | 12.4   | 23.1  | 3.19   | 3.97   |
| 2       | 17.0   | 7.5   | 18.1  | 19.9  | 4.4   | 7.3   | 18.1   | 22.5  | 2.93   | 3.79   |
| 3       | 12.0   | 9.8   | 19.8  | 19.3  | 3.9   | 9.4   | 14.0   | 20.2  | 2.64   | -      |
| 4       | 12.0   | 10.0  | 14.5  | 23.5  | 6.6   | 4.2   | 11.9   | 25.1  | -      | -      |
| 5       | 14.0   | 4.3   | 15.4  | 24.3  | 6.3   | 6.3   | 20.7   | 24.9  | 3.05   | 3.96   |
| 6       | 16.0   | -     | -     | -     | -     | -     | -      | -     | -      | 3.21   |
| 7       | 10.0   | -     | -     | -     | -     | -     | -      | -     | 2.51   | 3.12   |
| 8       | 15.0   | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| 9       | 12.0   | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| 10      | 13.0   | -     | -     | -     | -     | -     | -      | -     | -      | -      |
| Average | 13.4   | 8.0   | 16.7  | 19.7  | 6.5   | 6.5   | 15.4   | 23.2  | 2.86   | 3.61   |
| St.dev  | 2.1    | 2.3   | 2.2   | 5.0   | 2.8   | 2.0   | 3.8    | 2.0   |        |        |

\*Not included to analyses

Mean value of all 2018 tested values was 0.092 N/mm<sup>2</sup> whereas standard deviation was 0.023 N/mm<sup>2</sup>. It should be noted that the tension strength of this panel patch seems to be quite low and would not meet current requirements. Tensile strength is not usually critical factor in panel design and thus this information does not have that importance. Anyway, it can be concluded that average tensile strength of 2018 measured values was 59% higher than the original one. Average modulus of elasticity of all 2018 test is 13.4 N/mm<sup>2</sup> that is same as in 2007 result, but on the other hand, variation is quite high.

### 3.2.4 Bending tests

The bending test is used to determine the bending loading capacity and the associated wrinkling strength with a 6-point-bending test. For this, the limit load  $F_u$  is considered, to which the dead weight of the sandwich panel and the load introduction must be added. The bending moment  $M_u$  and the wrinkling strength  $\sigma_w$  is calculated according to equation (3).

$$M_u = \frac{F_u L}{8} \text{ and } \sigma_w = \frac{M_u}{e A_{F1}} \quad (3)$$

Where  $F_u$  is the maximum load,  $L$  is span length,  $M_u$  is maximum bending moment,  $e$  is the distance between the centres of gravity of the surface layers and  $A_{F1}$  is cross section of the face in compression.

Bending tests of MW panels were carried out with vacuum box to simulate equal loading (EN14509 [9] A.5). Test results are shown in Table 17 and in more detail in Annex B.

*Table 17 Measured values of wrinkling strength in bending tests [MPa]*

| Year    | 2007      | 2018             | 2020          |               |
|---------|-----------|------------------|---------------|---------------|
| Sample  | MW<br>Ref | MW<br>N2, N3, N6 | PIR<br>S1, S2 | PIR<br>W1, W2 |
| 1       | 150       | -                | 136           | 153           |
| 2       | 147       | 144              | 185           | 167           |
| 3       | 150       | 140              | -             | -             |
| 4       | 166       | -                | -             | -             |
| 5       | 152       | -                | -             | -             |
| 6       | -         | 127              |               |               |
| Average | 153       |                  | 161           | 160           |
| St.dev  | 7.5       |                  |               |               |

Failure mode in all MW tests was wrinkling failure partly inwards (2007 tests) and partly outwards (2018 tests) as presented in figures in Annex B and their wrinkling strength was lower than the strength measured in 2007. The measured strength of PIR panels is, on the other hand, higher than its declared value 142 MPa and 131 MPa for south and west panels respectively.

### 3.2.5 Shear tests

To determine the shear strength and the shear modulus, the load is applied to generate pure shear stress in the test specimen. EN 14509 A3.3 recommends a small span of 1000 mm to achieve a typical shear failure. The width of the specimen was 100 mm. The shear strength  $f_{cv}$  and the shear modulus  $G_c$  is calculated by equation (4).

$$f_{cv} = \frac{F_u}{2Be} \text{ and } G_c = F_u \frac{L}{6A_c \Delta w_s} \quad (4)$$

Where  $F_u$  is the maximum load,  $B$  is width of specimen,  $e$  is the distance between the centres of gravity of the surface layers,  $\Delta w_s$  is the slope of the linear part of the load-deflection curve,  $A_c$  is cross section of the core and  $L$  is span length of the specimen.

Shear tests of MW panels in 2007 test series were carried out according to EN14509 [9] Clause A.4. The 2018 tests were realized with vacuum box according to EN14509 [9] Clause 4.5. Test results are shown in Table 18 and in more detail in Annex B.

*Table 18 Measured values of shear strength and shear moduli in shear tests*

|           | Shear strength [MPa] |          |          |          |           |           | Shear modulus [MPa] |          |          |          |           |           |
|-----------|----------------------|----------|----------|----------|-----------|-----------|---------------------|----------|----------|----------|-----------|-----------|
| Year      | 2007                 | 2018     |          |          | 2020      |           | 2007                | 2018     |          |          | 2020      |           |
| Sample    | MW<br>Ref            | MW<br>S1 | MW<br>S2 | MW<br>S7 | PIR<br>S6 | PIR<br>W5 | MW<br>Ref           | MW<br>S1 | MW<br>S2 | MW<br>S7 | PIR<br>S6 | PIR<br>W5 |
| 1         | 0.063                | 0.046    | 0.066    | 0.070    | 0.130     | 0.152     | 2.5                 | 2.0      | 2.7      | 2.9      | 3.161     | 3.359     |
| 2         | 0.064                | -        | -        | -        | 0.131     | 0.144     | 2.7                 | -        | -        | -        | 2.934     | 3.082     |
| 3         | 0.067                | -        | -        | -        | 0.137     | 0.148     | 2.8                 | -        | -        | -        | 2.864     | 2.928     |
| 4         | 0.067                | -        | -        | -        | 0.131     | 0.151     | 2.4                 | -        | -        | -        | 2.782     | 3.301     |
| 5         | 0.068                | -        | -        | -        | -         | -         | 2.5                 | -        | -        | -        | -         | -         |
| 6         | 0.072                | -        | -        | -        | 0.135     | 0.147     | 2.5                 | -        | -        | -        | 2.728     | 3.066     |
| 7         | 0.071                | -        | -        | -        | 0.138     | -         | 2.8                 | -        | -        | -        | 2.961     | -         |
| 8         | 0.066                | -        | -        | -        | -         | -         | 2.6                 | -        | -        | -        | -         | -         |
| 9         | 0.065                | -        | -        | -        | -         | -         | 2.5                 | -        | -        | -        | -         | -         |
| Average   | 0.067                |          |          |          | 0.134     | 0.148     | 2.6                 |          |          |          | 2.905     | 3.141     |
| St.dev    | 0.003                |          |          |          |           |           |                     |          |          |          |           |           |
| 5% fract. |                      |          |          |          | 0.126     | 0.141     |                     |          |          |          | 2.568     | 2.731     |

Failure mode of all MW specimens was shear failure at lower face.

### 3.3 Tests on mechanical fasteners to one face of sandwich panel

The test programme was carried out to obtain information regarding the resistance of the fasteners used to fix additional elements to a face layer only of the sandwich panels. Test panels were old panels removed from the test building. Three types of self-drilling screws were studied in the test programme. The resistances with respect to tensile and shear loads were studied. The total number of individual tests was 18. Test programme was performed in the research hall of HAMK Tech Research Unit in Hämeenlinna between 8 and 14 May 2019. The tests were made by Mr. Silver Jänes and Mr. Lev Antimonik from HAMK University of Applied Sciences.

#### Test arrangement

The test specimens were tested by loading the fastening by a tensile or shear force. The loading was caused by the universal testing machine Zwick 50 kN. A special test jig was manufactured and fixed to the lower head of the testing machine. Test specimens were supported by the jig. The force applied to the specimen and the vertical displacement of the upper head of the testing machine was measured.

The arrangements are illustrated in Figure 24 in shear and in Figure 25 in tensile tests. In shear tests the width of the sheet metal strip, which was fixed to the panel by the studied fastener, was 30 mm. The free end of the strip was attached to the upper head of the testing machine. In tensile tests the upper head of the testing machine was attached to the tested screw using a special U-shaped fixing part. The studied fixture went through the bottom of the fixing part into the face of the panel. The head of the testing machine was connected to the fixing part using a M10 8.8 bolt.

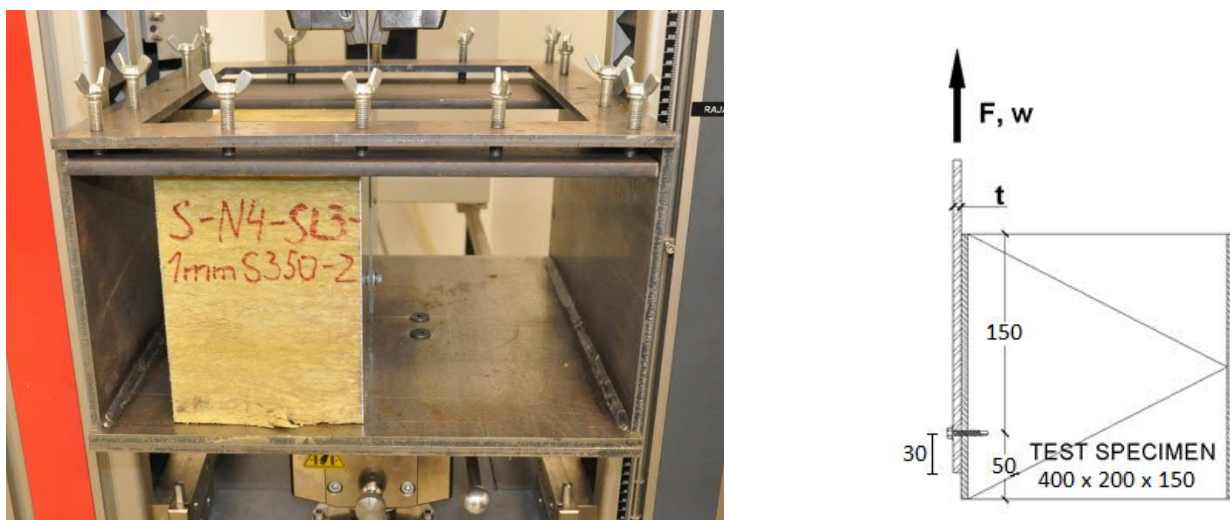


Figure 24 Test arrangements in shear tests

After tests on fasteners, 6 tensile test samples were extracted from exterior face layer material of the sandwich panel pieces: 3 from north and 3 from south side specimens. Samples were cut from panel pieces used in tensile tests. Face material is S280GD + Z275 PE. Purpose of these tests is to obtain information about material properties of surface material. Dimensions of test sample are presented in Figure 26.

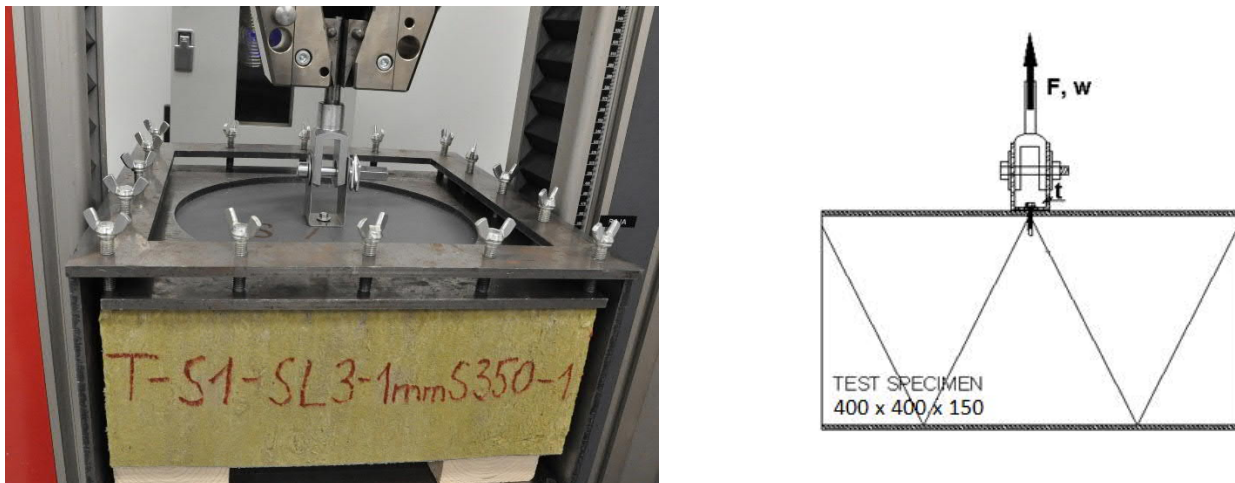


Figure 25 Test arrangement in tensile tests

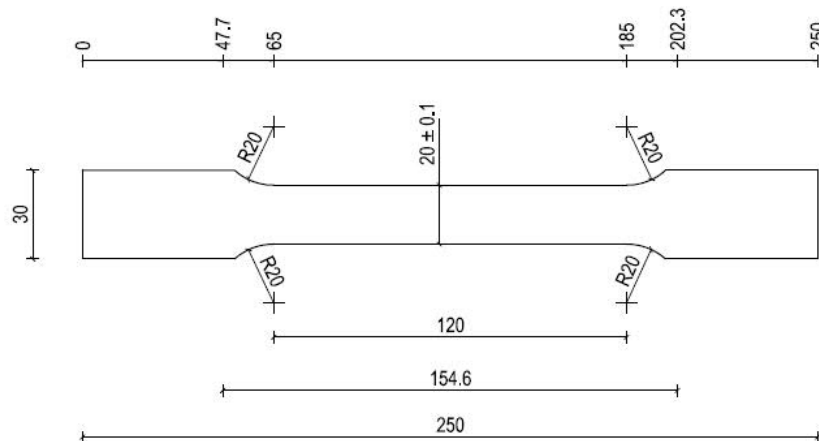


Figure 26 Tensile test sample for surface sheet material tests

## Results

Table 19 gives the mean resistances of the tested connections. Load versus displacement graphs are given in Appendix 2 and photographs in Appendix 3.

In shear test the failure mode was the bearing failure of the face sheet, and finally, the screw came out (i.e. pull-out failure). In the similar cases the resistances in the case of SL3-screw were higher than the resistances in the case of SL2-screw. S-N4-SL3-1mmS350-1 test was done with different test arrangement with steel plate with round hole in the middle (see Figure 47). Due to this panel's face layer has bent in several places during the test, test arrangement was changed after that. Photographs of test arrangement and panel damages are shown in Appendix 3. Plate with hole was substituted with two 400×100×10 mm plates at the sides of the panel. Image of new arrangement is presented in Figure 26.

In tensile tests the failure mode was pull-out failure in all cases. The resistances of the screws were at the same level and almost independent of the fixing plate type.

Tensile test results of surface material samples are presented in Table 20. Samples were extracted from T-N4-SL3 and T-S1-SL3 panel pieces. Stress versus strain graphs can be found in Appendix 3.

Table 19 Test results for shear and tensile tests in one face fixing tests

| Sample               | Test type | Panel | Fastener         | Sheet metal fixing | Force [N] | Average [N] | St.dev [N] |
|----------------------|-----------|-------|------------------|--------------------|-----------|-------------|------------|
| S-N4-SL3-1mmS350-1   | Shear     | N4    | SL3              | S350<br>t=1.0 mm   | 3053.2    | 3139.98     | 136.57     |
| S-N4-SL3-1mmS350-1-1 |           |       |                  |                    | 3157.3    |             |            |
| S-N4-SL3-1mmS350-2   |           |       |                  |                    | 3174.9    |             |            |
| S-N4-SL3-1mmS350-3   |           |       |                  |                    | 3337.5    |             |            |
| S-N4-SL3-1mmS350-4   |           |       |                  |                    | 2977.0    |             |            |
| S-S3-SL3-1mmS350-1   |           | S3    |                  |                    | 3373.1    | 3054.49     | 310.54     |
| S-S3-SL3-1mmS350-2   |           |       |                  |                    | 3037.7    |             |            |
| S-S3-SL3-1mmS350-3   |           |       |                  |                    | 2752.7    |             |            |
| T-N4-SL3-1mmS350-1   | Tensile   | N4    | SL3              | S350<br>t=1.0 mm   | 1151.8    | 1184.26     | 60.10      |
| T-N4-SL3-1mmS350-2   |           |       |                  |                    | 1253.6    |             |            |
| T-N4-SL3-1mmS350-3   |           |       |                  |                    | 1147.4    |             |            |
| T-S1-SL3-1mmS350-1   |           | S1    |                  |                    | 1149.4    | 1153.85     | 17.95      |
| T-S1-SL3-1mmS350-2   |           |       |                  |                    | 1173.6    |             |            |
| T-S1-SL3-1mmS350-3   |           |       |                  |                    | 1138.6    |             |            |
| T-S1-SL2-0_6mmS280-1 |           | SL2   | S280<br>t=0.6 mm | 1161.9             | 1124.60   | 52.80       |            |
| T-S1-SL2-0_6mmS280-2 |           |       |                  | 1087.3             |           |             |            |
| T-N4-SL2-0_6mmS280-1 |           |       |                  | N4                 | 1125.1    | 1105.54     | 27.64      |
| T-N5-SL2-0_6mmS280-2 |           |       |                  | N5                 | 1086.0    |             |            |

Table 20 Tensile test results for outer surface steel sheet

| Sample | Direction | $a_0$<br>[mm] | $b_0$<br>[mm] | $S_0$<br>[mm <sup>2</sup> ] | $E$<br>[GPa] | $R_{p0.2}$<br>[MPa] | $R_{eH}$<br>[MPa] | $R_{eL}$<br>[MPa] | $R_m$<br>[MPa] |
|--------|-----------|---------------|---------------|-----------------------------|--------------|---------------------|-------------------|-------------------|----------------|
| 1      | North     | 0.56          | 19.65         | 11                          | 201          | 426                 | 429               | 419               | 488            |
| 2      | North     | 0.56          | 19.64         | 11                          | 182          | 414                 | 414               | 411               | 487            |
| 3      | North     | 0.56          | 19.67         | 11.02                       | 213          | 422                 | 421               | 413               | 487            |
| 4      | South     | 0.553         | 19.58         | 10.83                       | 192          | 350                 | -                 | -                 | 449            |
| 5      | South     | 0.56          | 19.57         | 10.96                       | 199          | 351                 | 352               | 350               | 448            |
| 6      | South     | 0.553         | 19.59         | 10.83                       | 190          | 350                 | 350               | 348               | 448            |

Test results were compared also to the tests for new panels performed in years 2009 and 2010. Current shear test results were almost 70% better than the test results in previous tests. It should be noted that the core material was not exactly same in these test series. In tensile tests difference was lower. In the case of 0.6 mm cases current mean results were exactly same as in the previous tests and in the case of 1.0 mm cases current results were 11% weaker than in 2009 and 2010 series.

### 3.4 Thermal resistance/conductivity ( $\lambda$ ) tests

Lambda values of totally three pieces (600 mm \* 600 mm \* 140 mm) of mineral wool insulation were tested at Eurofins Expert Services in Finland. The test pieces were removed from Panels N4 and S7. Pictures of the test specimen are shown in Figure 27.

The tests were performed according to the standard EN 12667 [10], "Building materials – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance". The apparatus used was in accordance with the standard ISO 8301 [11].

During the test, the specimen was in horizontal position and the heat flow was vertical. The tests were performed at mean temperature of +10 °C. The test results are shown in Table 21.



Figure 27 Lamda test specimen

Table 21 The thermal conductivities for the studied specimen

| Product | Thickness<br>d<br>(mm) | Dry<br>weight<br>m <sub>1</sub><br>(g) | Weight<br>after<br>test<br>m <sub>2</sub><br>(g) | Dry<br>density<br>ρ<br>kg/m <sup>3</sup> | Mean<br>temperature<br>T <sub>m</sub><br>°C | Temperature<br>difference<br>ΔT<br>K | Density<br>of heat flow<br>q<br>W/m <sup>2</sup> | Thermal<br>resistance<br>R<br>(m <sup>2</sup> K)/W | Thermal<br>conductivity<br>λ <sub>10</sub><br>W/(m · K) |
|---------|------------------------|----------------------------------------|--------------------------------------------------|------------------------------------------|---------------------------------------------|--------------------------------------|--------------------------------------------------|----------------------------------------------------|---------------------------------------------------------|
| S7-1    | 143,0                  | 6118                                   | 6120                                             | 116,9                                    | 9,94                                        | 20,07                                | 5,832                                            | 3,440                                              | <b>0,0416</b>                                           |
| S7-2    | 143,3                  | 6151                                   | 6148                                             | 116,9                                    | 9,93                                        | 20,05                                | 5,832                                            | 3,438                                              | <b>0,0417</b>                                           |
| N4      | 143,6                  | 6155                                   | 6152                                             | 117,7                                    | 9,93                                        | 20,06                                | 5,845                                            | 3,433                                              | <b>0,0418</b>                                           |

Mean value of the thermal conductivity was  $\lambda_{10} = 0.0417$  W/(m·K). All the measured values were well lower than the declared value  $\lambda_D = 0.045$  W/(m·K) (based on  $\lambda_{90/90}$  of the manufacturer for the Paroc CES 50 CS100 insulation provided in the production time 2007).

## 4 Summary and conclusions

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The report summarizes results of 269 experiments on structural steel sections and sandwich panels removed from four buildings of different age. The results of structural steel tests showed a good agreement with the expected values with the exception of specimen produced in 1930s before the current steel quality standards were developed, where the main barrier for reuse was its poor weldability due to the unsuitable chemical composition. The tests of sandwich panels showed signs of degradation caused by ageing, but the main problem was typically large variation of the test results.

The second goal of this study was to demonstrate the full package of minimum invasive material tests that will not compromise the integrity of structural components and can be performed before deconstruction. Hardness, chemical and sub-sized impact tests are already well-established, but the methods to determine material yield and tensile strength and ductility are still being developed. In this report, two experimental approaches were used for this purpose: small punch test and instrumented indentation test. According to the literature review, both methods were already successfully tested for similar applications and both methods can be used on-site with portable testing apparatus. Moreover, the small punch test method is in the standardization process.

It can be concluded that small punch tests could determine yield and tensile strength with acceptable accuracy and the variation of the test results was surprisingly low. On the other hand, it was impossible to use the documented method for prediction of material strength from the indentation tests. Therefore, it is recommended to study the indentation method further. Both test methods provide load-displacement measurements that can be alternatively converted into stress-strain relationship using more sophisticated reverse Finite Element Modelling.

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## Annex A Small punch tests results

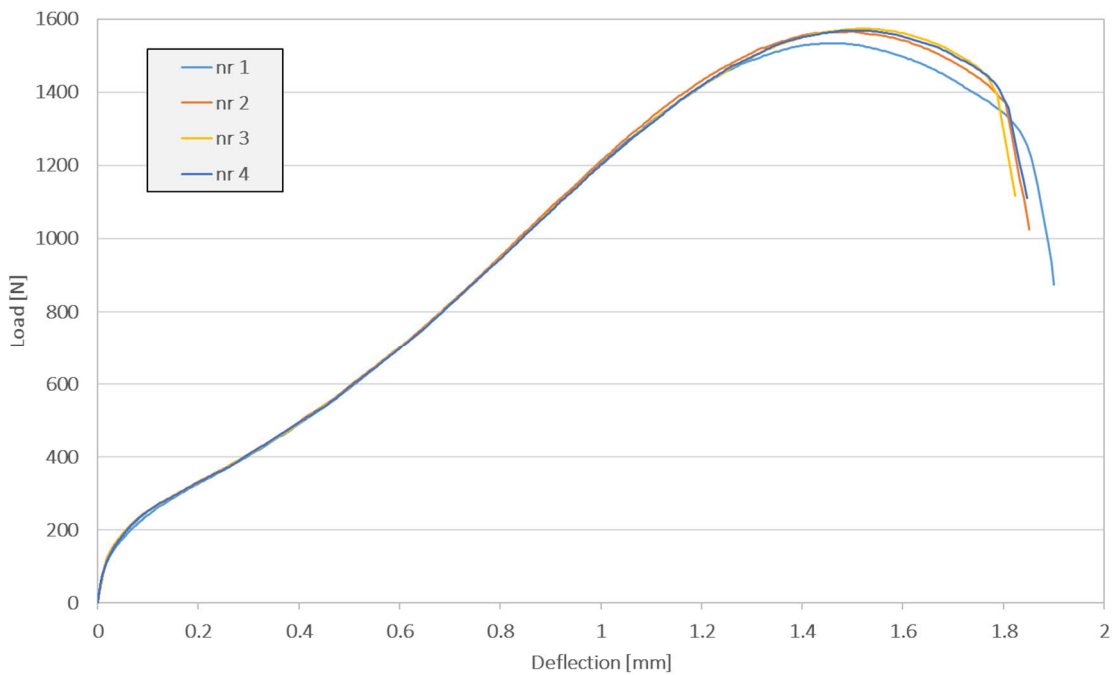


Figure 28. Load – deflection curves of tensile Sample 1.

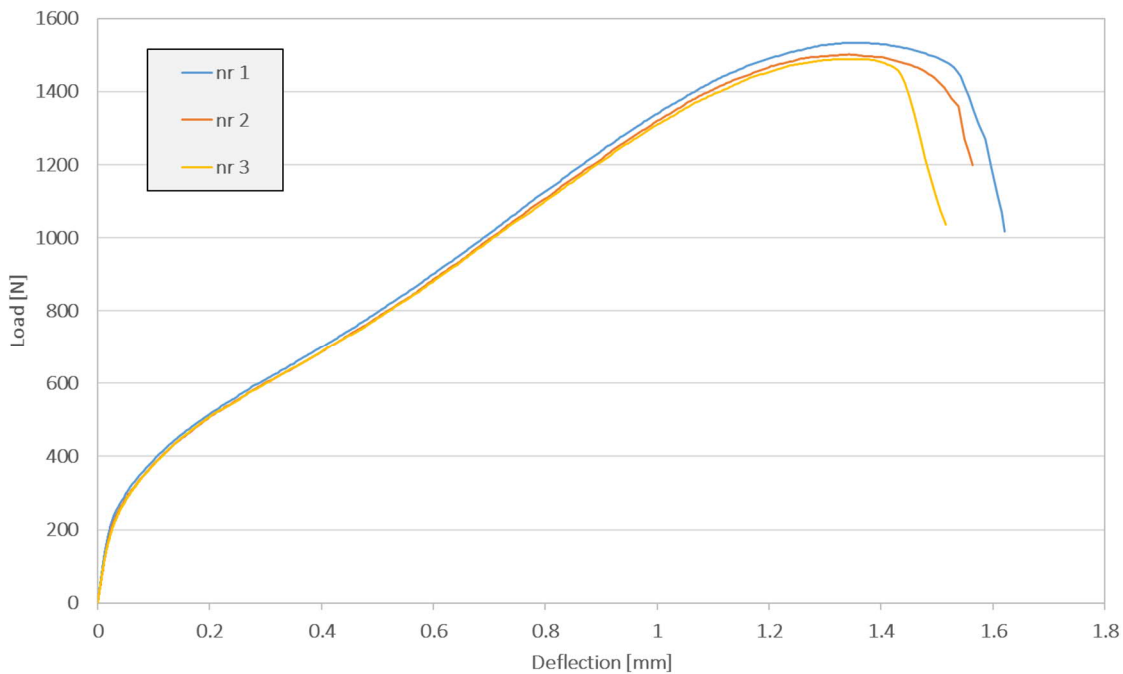


Figure 29. Load – deflection curves of tensile Sample 2.

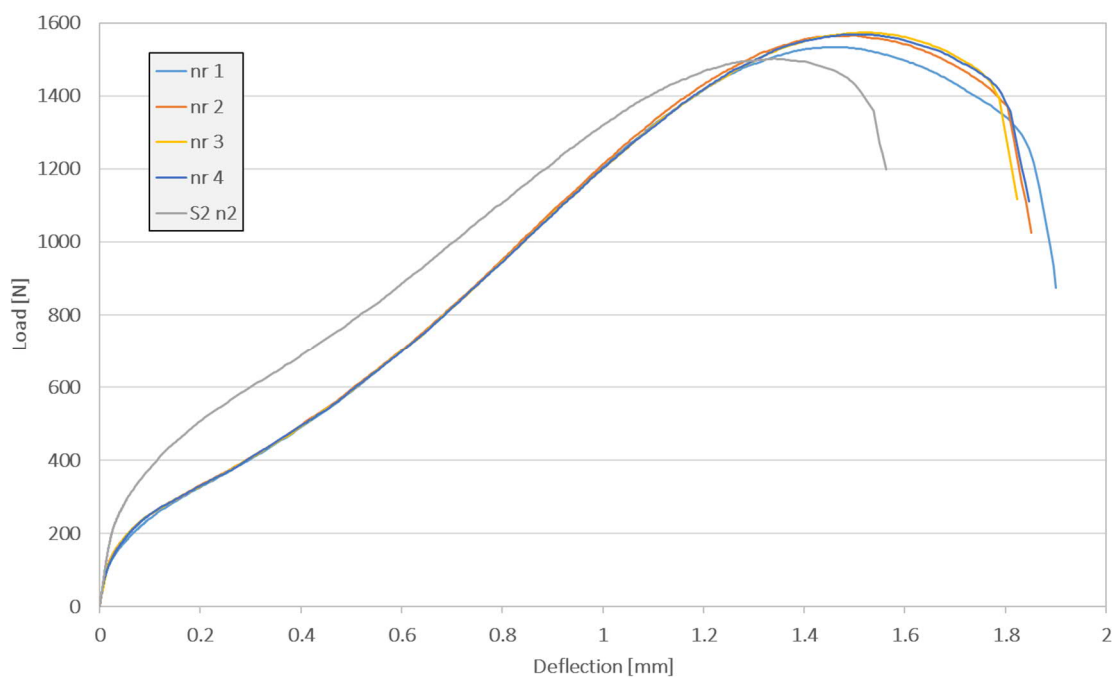


Figure 30. Comparison of Sample 2 specimen nr 2 load curve with the load curves from Sample 1.

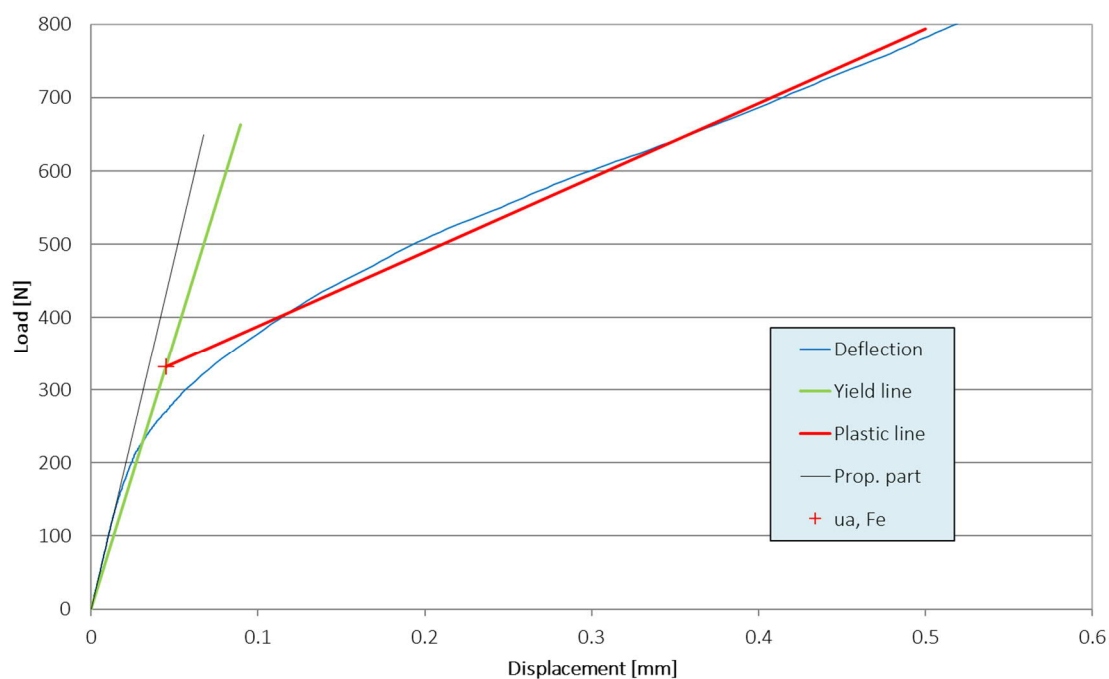


Figure 31. Example of definition of yield load determination from the tensile curve.

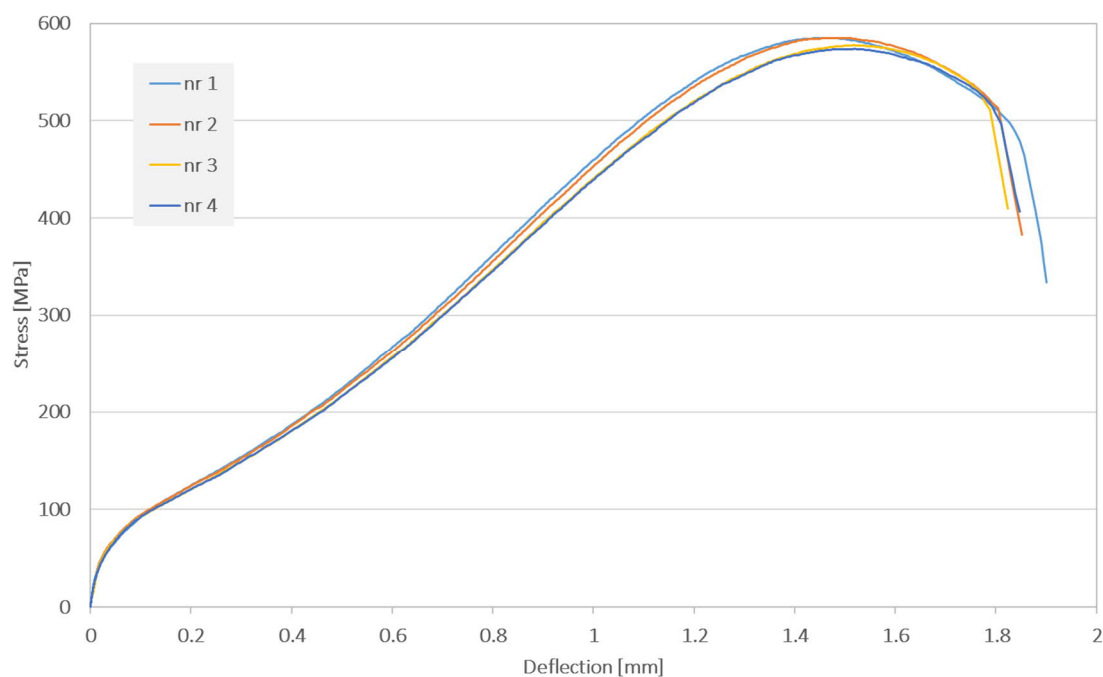


Figure 32. Stress – deflection curves of Sample 1 calculated by Equation C.1.

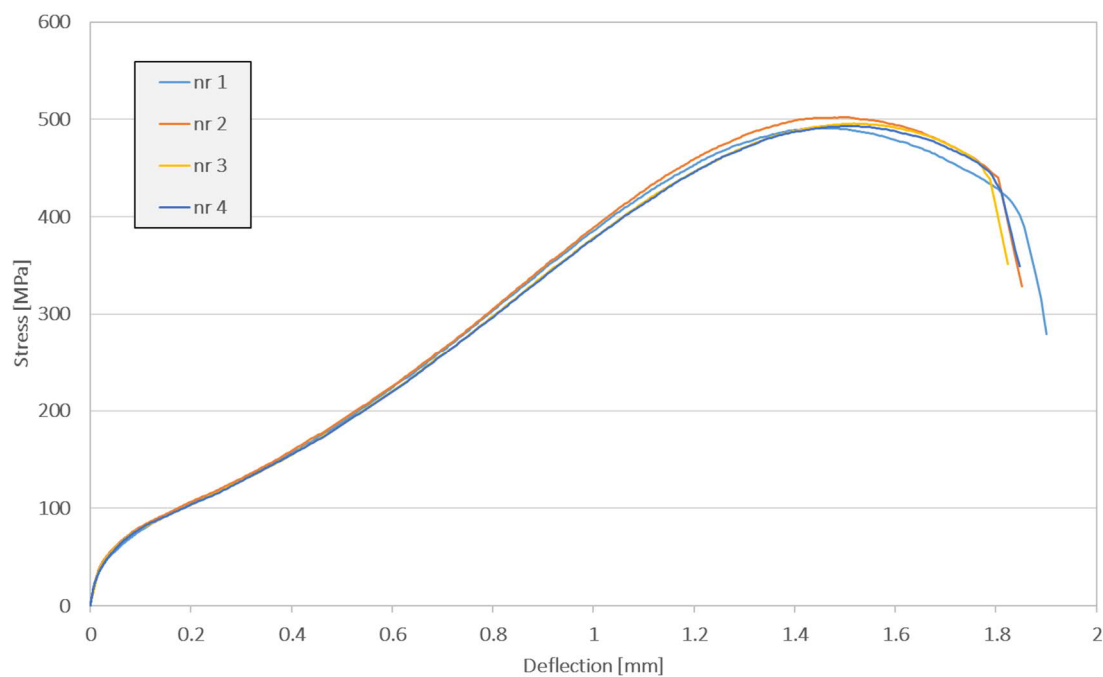


Figure 33. Stress – deflection curves of Sample 1 calculated by Equation C.2.

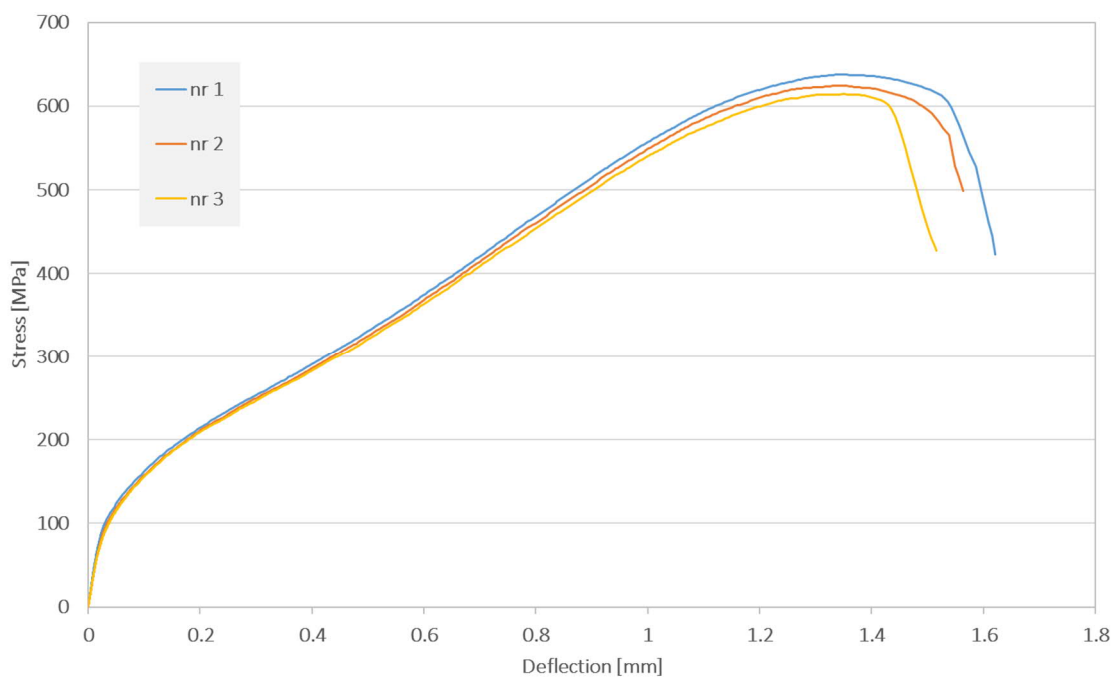


Figure 34. Stress – deflection curves of Sample 2 calculated by Equation C.1

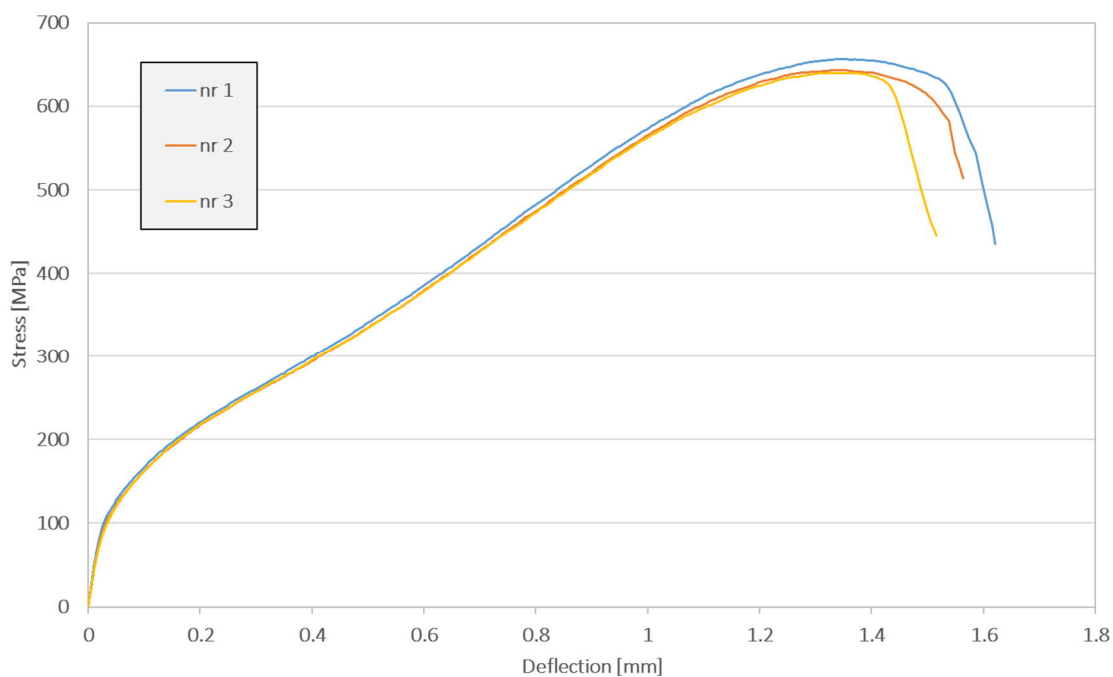


Figure 35. Stress – deflection curves of Sample 2 calculated by Equation C.2.

## Annex B Sandwich panels mechanical testing results

Table 22 Tensile test results PIR panels south side (PIR-S3)

| Specimen     | Max. Load<br>[N] | Elongation<br>[%] | Tensile Strength<br>[MPa]  | Tensile Modulus<br>[MPa] |
|--------------|------------------|-------------------|----------------------------|--------------------------|
| 1            | 1824.65          | 2.15              | 0.078                      | 3.19                     |
| 2            | 1127.19          | 1.63              | -                          | 2.93                     |
| 3            | 1019.94          | 1.96              | -                          | 2.64                     |
| 5            | 1736.22          | 2.78              | 0.076                      | 3.05                     |
| 6            | 1542.68          | 2.64              | 0.064                      | -                        |
| 7            | 1329.11          | 2.42              | 0.059                      | 2.51                     |
| Test results | Average          |                   | 0.069                      | 2.864                    |
|              | 5%-fractile      |                   | 0.048                      | 2.230                    |
| Declared     | Average          |                   | -                          | 3.57 <sup>2)</sup>       |
|              | 5%-fractile      |                   | 0.08 (0.04 <sup>1)</sup> ) | 2.93 <sup>2)</sup>       |

<sup>1)</sup> According to EN 14509 [9] a decrease of 50 % of tensile load is acceptable

<sup>2)</sup> No values for tensile modulus declared;  $E_c = 3,8 = 0,5 \cdot (E_{ct} + E_{cc})$

Table 23 Tensile test results PIR panels west side (PIR-W3)

| Specimen     | Max. Load<br>[N] | Elongation<br>[%] | Tensile Strength<br>[MPa]  | Tensile Modulus<br>[MPa] |
|--------------|------------------|-------------------|----------------------------|--------------------------|
| 1            | 1630.22          | 1.93              | 0.071                      | 3.97                     |
| 2            | 1729.28          | 1.99              | 0.076                      | 3.79                     |
| 5            | 2275.94          | 2.45              | 0.101                      | 3.96                     |
| 6            | 1759.30          | 3.01              | 0.077                      | 3.21                     |
| 7            | 1763.72          | 2.96              | 0.078                      | 3.12                     |
| Test results | Average          |                   | 0.080                      | 3.610                    |
|              | 5%-fractile      |                   | 0.057                      | 2.692                    |
| Declared     | Average          |                   | -                          | 3.8                      |
|              | 5%-fractile      |                   | 0.08 (0.04 <sup>1)</sup> ) | 3.3                      |

<sup>1)</sup> According to EN 14509 [9] a decrease of 50 % of tensile load is acceptable

*Table 24 Compressive test results PIR panels south side (PIR-S3)*

| Specimen     | Max. Load<br>[kN]  | Compressive<br>Modulus<br>[MPa] | Compressive<br>Strength<br>[MPa] |
|--------------|--------------------|---------------------------------|----------------------------------|
| 1            | 2.76               | 3.01                            | 0.125                            |
| 2            | 2.58               | 3.00                            | 0.117                            |
| 3            | 2.95               | 3.07                            | 0.131                            |
| 4            | 2.86               | 3.20                            | 0.129                            |
| 5            | 3.17               | 3.15                            | 0.140                            |
| Test results | <b>Average</b>     | <b>3.086</b>                    | <b>0.128</b>                     |
|              | <b>5%-fractile</b> | <b>2.881</b>                    | <b>0.109</b>                     |
| Declared     | <b>Average</b>     | <b>3.57</b>                     | <b>-</b>                         |
|              | <b>5%-fractile</b> | <b>2.93</b>                     | <b>0.10</b>                      |

*Table 25 Compressive test results PIR panels west side (PIR-W3)*

| Specimen     | Max. Load<br>[kN]  | Compressive<br>Modulus<br>[MPa] | Compressive<br>Strength<br>[MPa] |
|--------------|--------------------|---------------------------------|----------------------------------|
| 1            | 3.66               | 3.66                            | 0.165                            |
| 2            | 3.51               | 3.75                            | 0.159                            |
| 3            | 3.59               | 3.58                            | 0.163                            |
| 4            | 3.61               | 3.59                            | 0.164                            |
| 5            | 3.57               | 3.77                            | 0.162                            |
| Test results | <b>Average</b>     | <b>3.67</b>                     | <b>0.163</b>                     |
|              | <b>5%-fractile</b> | <b>3.46</b>                     | <b>0.157</b>                     |
| Declared     | <b>Average</b>     | <b>-</b>                        | <b>-</b>                         |
|              | <b>5%-fractile</b> | <b>2.50</b>                     | <b>0.10</b>                      |

Table 26 Results of MW panels bending test 2007

| Sample    | Panel length<br>[mm] | Max. load<br>[kN] | Max. deflection<br>[mm] | Location of failure<br>[mm] | Wrinkling strength at midspan<br>[MPa] | Shear strength at support<br>[MPa] | Shear modulus<br>[MPa] |
|-----------|----------------------|-------------------|-------------------------|-----------------------------|----------------------------------------|------------------------------------|------------------------|
| 980260-3  | 5080                 | 22.83             | 52                      | 2460                        | 150                                    | 0.063                              | 2.9                    |
| 980260-5  | 6500                 | 17.36             | 57                      | 3140                        | 147                                    | 0.048                              | 3.0                    |
| 980260-6K | 6500                 | 17.68             | 51                      | 2700                        | 150                                    | 0.049                              | 4.2                    |
| 980260-7K | 6500                 | 19.55             | 56                      | 2850                        | 166                                    | 0.054                              | 4.4                    |
| 980260-8  | 6500                 | 17.92             | 56                      | 2600                        | 152                                    | 0.050                              | 3.3                    |
| Average   |                      |                   |                         |                             | 153                                    |                                    | 3.6                    |
| St.dev    |                      |                   |                         |                             | 7.5                                    |                                    |                        |

Table 27 Results of dismantled MW panels bending tests 2018

| Sample  | Panel length<br>[mm] | Max. load<br>[kN] | Max. deflection<br>[mm] | Location of failure<br>[mm] | Wrinkling strength at midspan<br>[MPa] | Shear strength at support<br>[MPa] | Shear modulus<br>[MPa] |
|---------|----------------------|-------------------|-------------------------|-----------------------------|----------------------------------------|------------------------------------|------------------------|
| MW-N2   | 5070                 | 24.3              | 57.6                    | 1000                        | 144.4                                  |                                    | 2.8                    |
| MW-N3   | 5070                 | 23.5              | 44.1                    | 1900                        | 139.7                                  |                                    | 3.4                    |
| MW-N6   | 5070                 | 21.4              | 39.3                    | 2500                        | 127.2                                  | 0.058                              | 3.6                    |
| Average |                      |                   |                         |                             | 137.1                                  |                                    | 3.2                    |
| St.dev  |                      |                   |                         |                             | 8.9                                    |                                    |                        |

Table 28 Results of dismantled PIR panels bending tests 2018

| Specimen  | Max. Load<br>[kN]t | Displacement<br>[mm] | Wrinkling Strength<br>[MPa] | Wrinkling Strength Declared<br>[MPa] |
|-----------|--------------------|----------------------|-----------------------------|--------------------------------------|
| PIR-S3 01 | 10.1               | 121.3                | 135.8                       | 142                                  |
| PIR-S3 02 | 13.7               | 114.1                | 184.6                       |                                      |
| PIR-W3 01 | 11.92              | 131.76               | 152.91                      | 131                                  |
| PIR-W3 02 | 13.01              | 98.87                | 166.90                      |                                      |

*Table 29 Results of MW panels shear test 2007*

| Sample     | Panel length<br>[mm] | Max. load<br>[kN] | Max. deflection<br>[mm] | Location of failure<br>[mm] | Wrinkling strength at midspan<br>[MPa] | Shear strength at support<br>[MPa] | Shear modulus<br>[MPa] |
|------------|----------------------|-------------------|-------------------------|-----------------------------|----------------------------------------|------------------------------------|------------------------|
| 980260-1   | 5080                 | 23.05             | 63                      | 100                         | 145                                    | <b>0.063</b>                       | 2.5                    |
| 980260-2   | 5080                 | 23.69             | 60                      | 100                         | 150                                    | <b>0.064</b>                       | 2.7                    |
| 980260-4K  | 5080                 | 24.52             | 57                      | 150                         | 155                                    | <b>0.067</b>                       | 2.8                    |
| 980260-9   | 3000                 | 25.28             | 30                      | 100                         | 89                                     | <b>0.067</b>                       | 2.4                    |
| 980260-10  | 3000                 | 25.73             | 28                      | 200                         | 90                                     | <b>0.068</b>                       | 2.5                    |
| 980260-11K | 3000                 | 27.12             | 31                      | 100                         | 95                                     | <b>0.072</b>                       | 2.5                    |
| 980260-12K | 3800                 | 26.34             | 40                      | 130                         | 121                                    | <b>0.071</b>                       | 2.8                    |
| 980260-13  | 3800                 | 24.41             | 39                      | 100                         | 112                                    | <b>0.066</b>                       | 2.6                    |
| 980260-14  | 3800                 | 24.22             | 35                      | 150                         | 111                                    | <b>0.065</b>                       | 2.5                    |
| Avg.       |                      |                   |                         |                             |                                        | <b>0.067</b>                       | 2.6                    |
| St.dev.    |                      |                   |                         |                             |                                        | <b>0.003</b>                       |                        |

*Table 30 Results of dismantled MW panels shear tests 2018*

| Sample  | Panel length<br>[mm] | Max. load<br>[kN] | Max. deflection<br>[mm] | Location of failure<br>[mm] | Wrinkling strength at midspan<br>[MPa] | Shear strength at support<br>[MPa] | Shear modulus<br>[MPa] |
|---------|----------------------|-------------------|-------------------------|-----------------------------|----------------------------------------|------------------------------------|------------------------|
| MW-S1   | 3800                 | 16.8              | 33.3                    | 150                         | 75.9                                   | <b>0.046</b>                       | 2.0                    |
| MW-S2   | 3800                 | 25.1              | 34.8                    | 200                         | 107.2                                  | <b>0.066</b>                       | 2.7                    |
| MW-S7   | 3800                 | 26.6              | 36.3                    | 250                         | 113.6                                  | <b>0.070</b>                       | 2.9                    |
| Average |                      |                   |                         |                             |                                        | <b>0.061</b>                       | 2.5                    |
| St.dev  |                      |                   |                         |                             |                                        | <b>0.013</b>                       |                        |

Table 31 Shear test results, PIR panels south side

| Specimen     | Max. Load<br>[N]   | Displacement<br>[mm] | Shear Strength<br>[MPa] | Shear Modulus<br>[MPa] |
|--------------|--------------------|----------------------|-------------------------|------------------------|
| S01          | 2473.03            | 17.06                | 0.130                   | 3.161                  |
| S02          | 2491.93            | 20.28                | 0.131                   | 2.934                  |
| S03          | 2622.38            | 25.46                | 0.137                   | 2.864                  |
| S04          | 2486.28            | 21.09                | 0.131                   | 2.782                  |
| S06          | 2552.99            | 22.36                | 0.135                   | 2.728                  |
| S07          | 2611.80            | 20.73                | 0.138                   | 2.961                  |
| Test results | <b>Average</b>     |                      | <b>0.134</b>            | <b>2.905</b>           |
|              | <b>5%-fractile</b> |                      | <b>0.126</b>            | <b>2.568</b>           |
| Declared     | <b>Average</b>     |                      | <b>-</b>                | <b>3.500</b>           |
|              | <b>5%-fractile</b> |                      | <b>0.100</b>            | <b>3.070</b>           |

Table 32 Shear test results PIR panels west side

| Specimen     | Max. Load<br>[N]   | Displacement<br>[mm] | Shear Strength<br>[MPa] | Shear Modulus<br>[MPa] |
|--------------|--------------------|----------------------|-------------------------|------------------------|
| W01          | 2895.09            | 22.29                | 0.152                   | 3.359                  |
| W02          | 2768.75            | 20.71                | 0.144                   | 3.082                  |
| W03          | 2835.43            | 20.97                | 0.148                   | 2.928                  |
| W04          | 2904.42            | 22.35                | 0.151                   | 3.301                  |
| W06          | 2810.68            | 21.27                | 0.147                   | 3.066                  |
| Test results | <b>Average</b>     |                      | <b>0.148</b>            | <b>3.141</b>           |
|              | <b>5%-fractile</b> |                      | <b>0.141</b>            | <b>2.731</b>           |
| Declared     | <b>Average</b>     |                      | <b>-</b>                | <b>3.800</b>           |
|              | <b>5%-fractile</b> |                      | <b>0.130</b>            | <b>3.40</b>            |

Force versus displacement graphs for shear tests (S) and tensile tests (T)

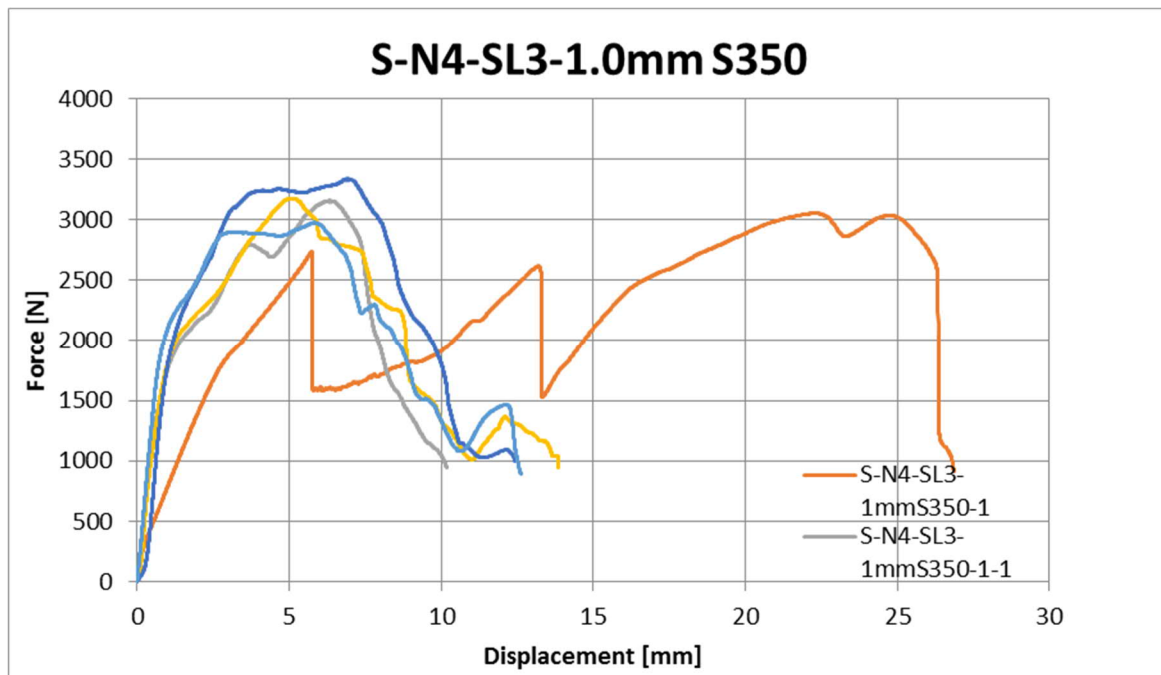


Figure 36 Load-displacement results from S-N4-SL3-1.0mm S350

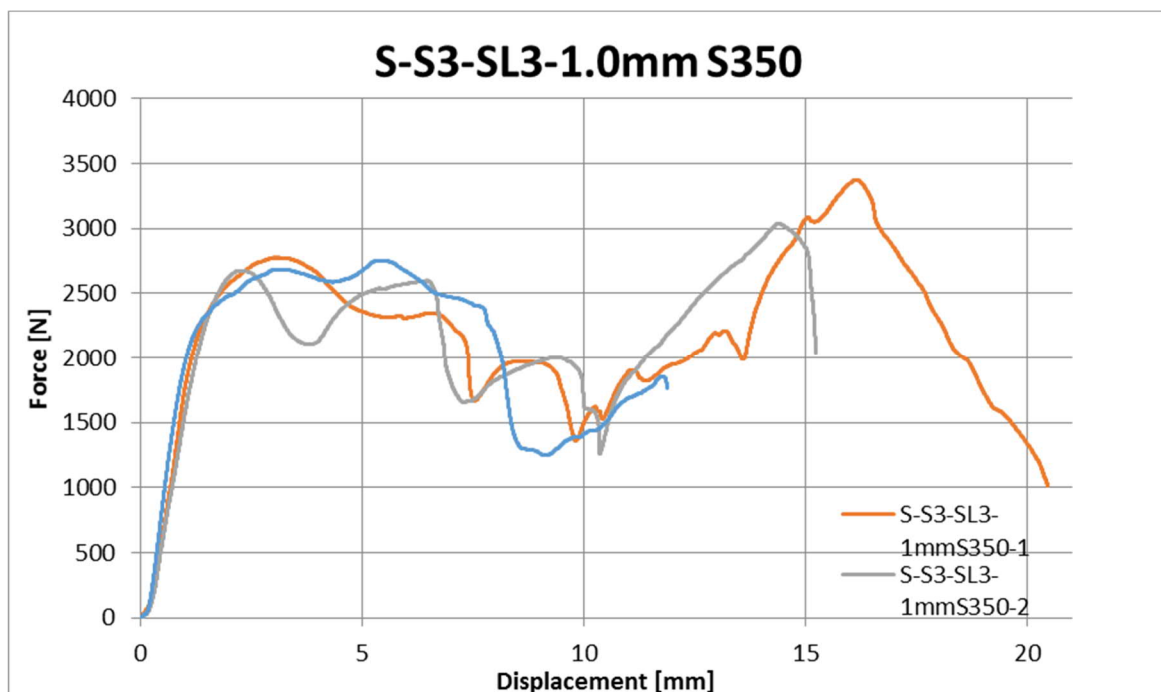


Figure 37 Load-displacement results from S-S3-SL3-1.0mm S350

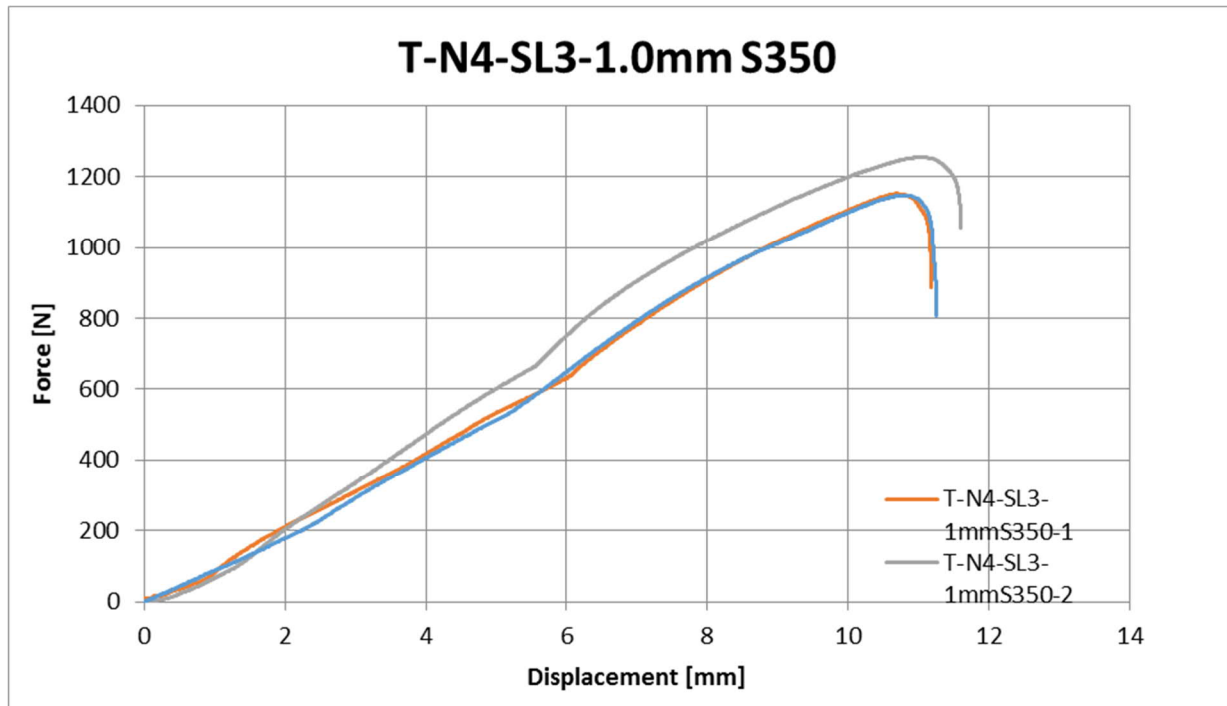


Figure 38 Load-displacement results from T-N4-SL3-1.0mm S350

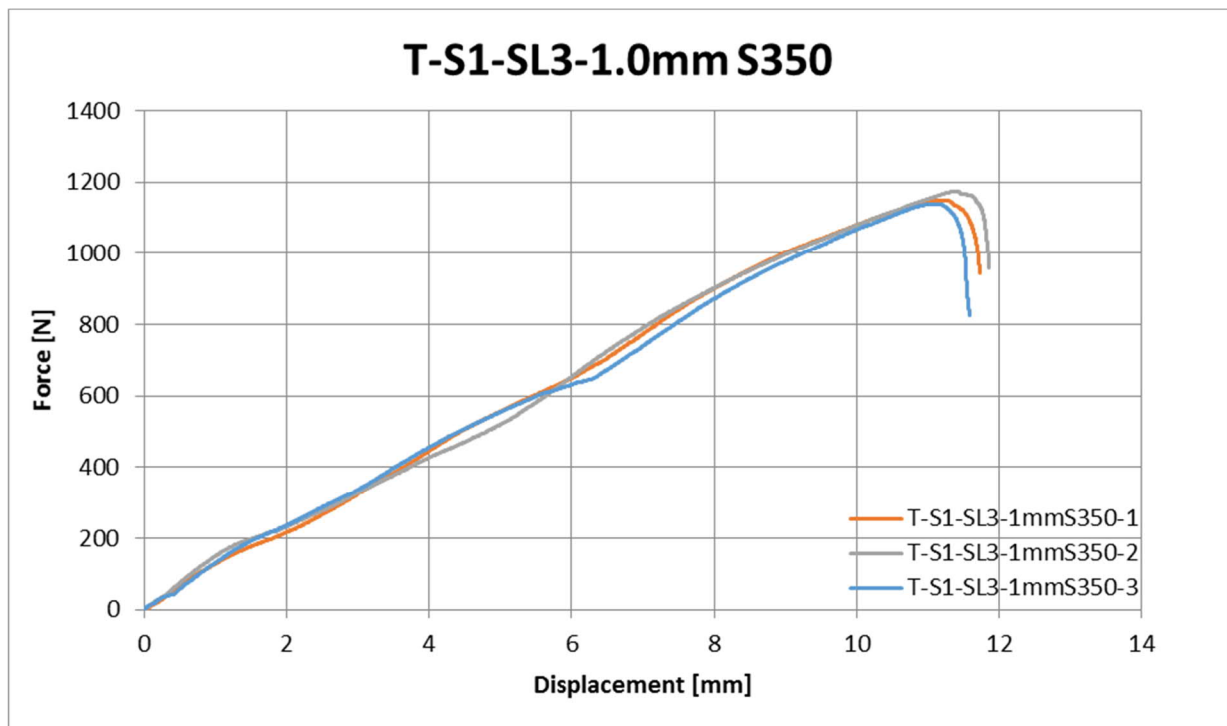


Figure 39 Load-displacement results from T-S1-SL3-1.0mm S350

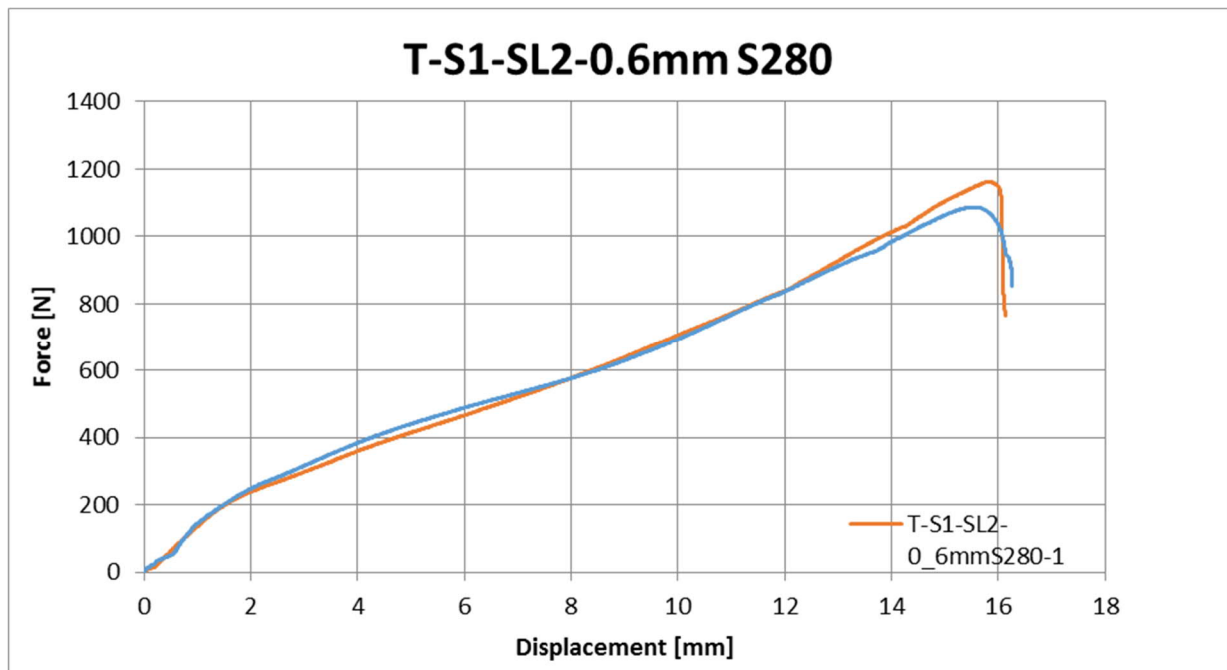


Figure 40 Load-displacement results from T-S1-SL2-0.6mm S280

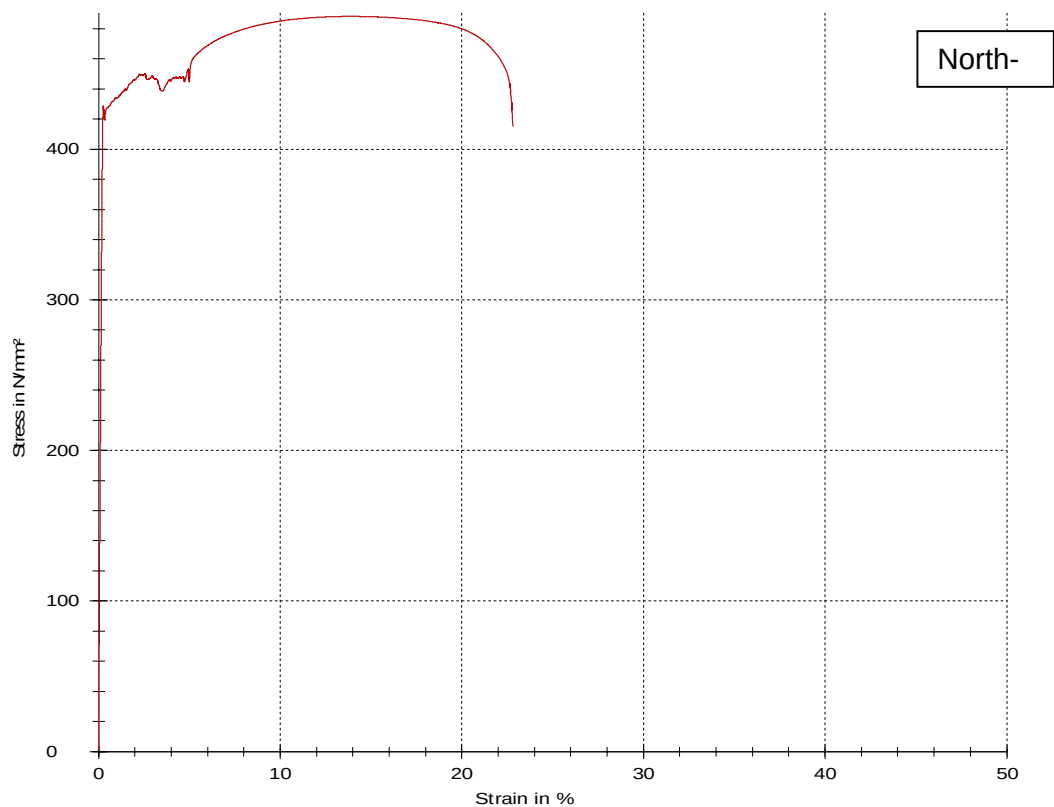
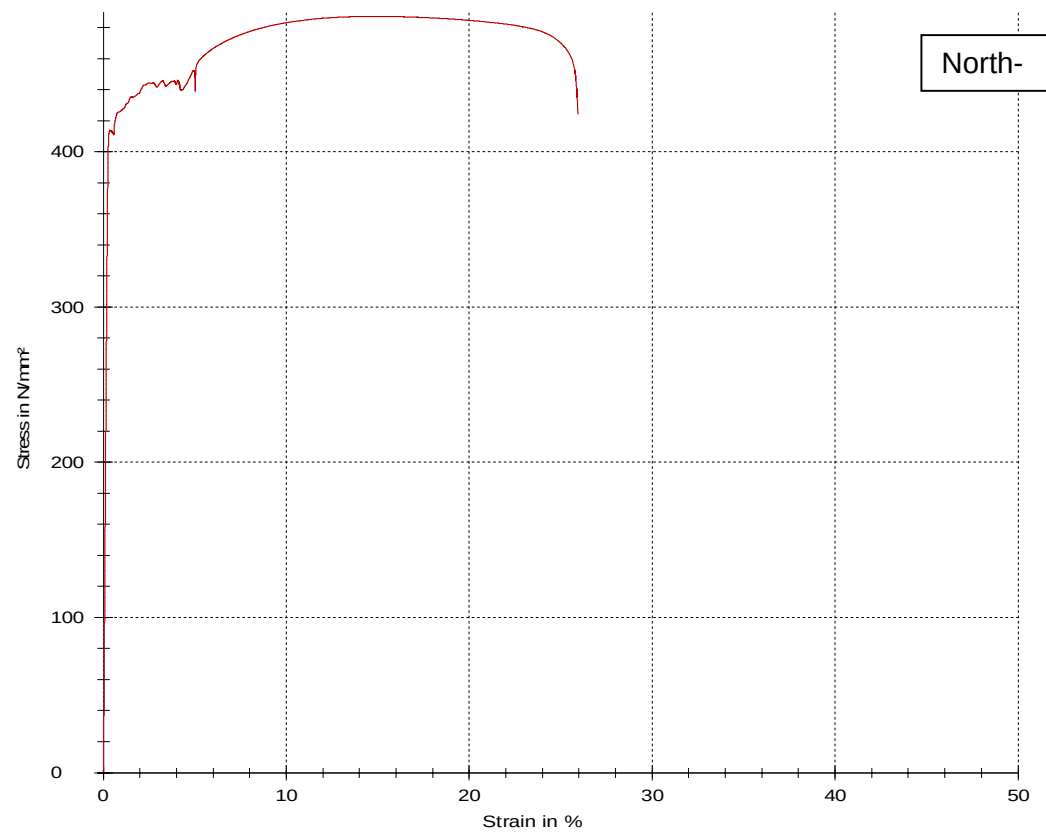
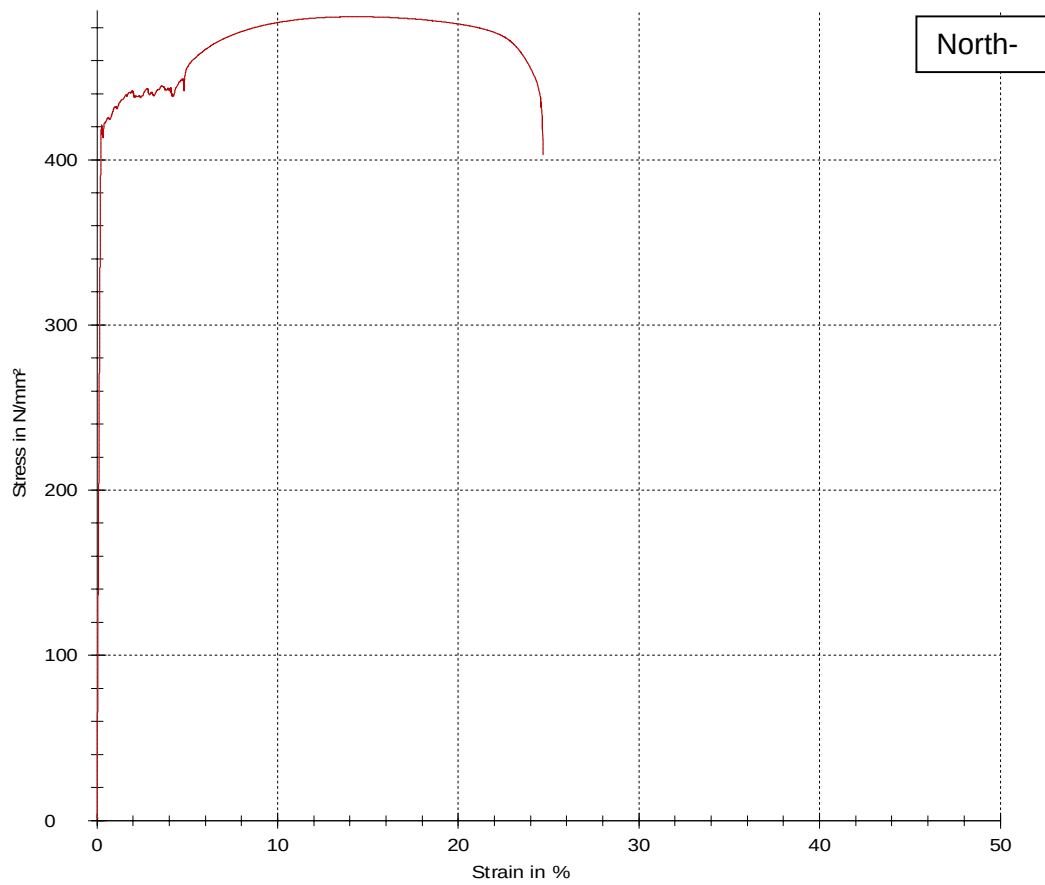


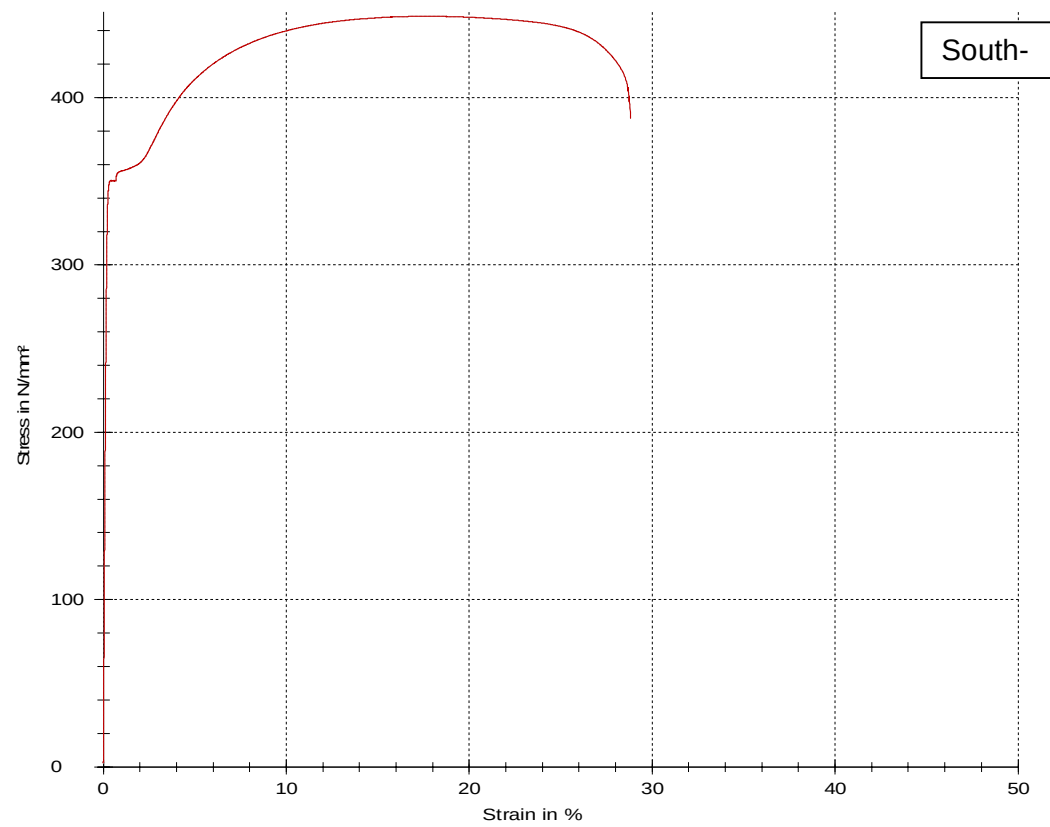
Figure 41 Stress-strain relationship



*Figure 42 Stress-strain relationship*



*Figure 43 Stress-strain relationship*



*Figure 44 Stress-strain relationship*

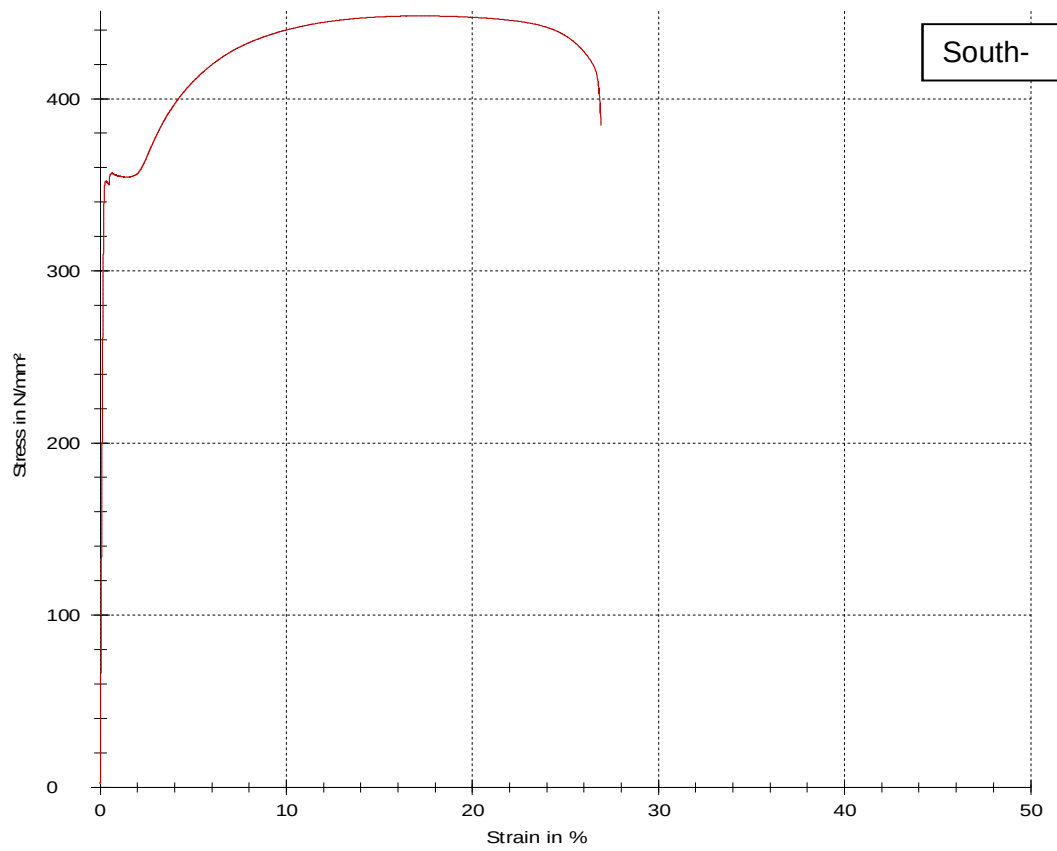
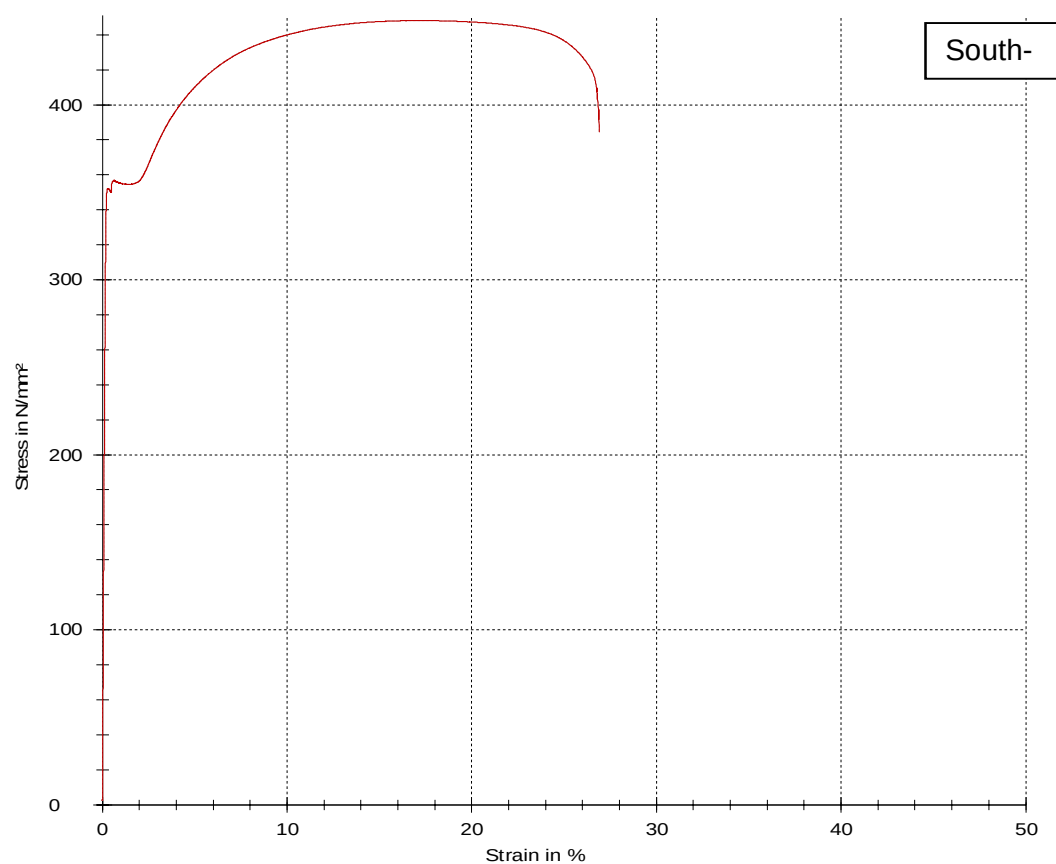


Figure 45 Stress-strain relationship



*Figure 46 Stress-strain relationship*

## Annex C Analysis of structural testing of sandwich panels

The number of available tested specimen was quite low and thus not all test series were able to perform. Proposed criteria for strength values of reusing sandwich panels are summarized in Table 33 followed by an evaluation is for tensile and shear strength.

Table 33 Proposed criteria for reused panels

| <b>Mechanical strength</b>                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Testing cross panel tensile strength 3 samples a minimum (EN 14509, A.1):<br>Calculate characteristic result for tensile strength<br>Testing one sample for shear strength (EN 14509, A.3 or A.4) |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Tensile strength $\geq 0,9^*$<br>Declared value of Tensile strength                                                                                                                               | <b>If YES:</b><br>No further testing. All declared values for mechanical strength can be used                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| and<br><br>Shear strength $\geq$ Declared value of Shear strength                                                                                                                                 | <b>If NO:</b><br>New declared values to be determined with a test program according to EN 14509 for<br>- Tensile strength<br>- Compression strength<br>- Shear strength<br>The wrinkling strength is reduced with same amount that shear strength is reduced.                                                                                                                                                                                                                                                                                      |
| <b>Durability</b>                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Tensile strength $\geq 0,9^*$<br>Declared value of Tensile strength                                                                                                                               | <b>If YES:</b><br>No further testing; panels are fit for use                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|                                                                                                                                                                                                   | <b>If NO:</b><br><u>MW panels:</u><br>The 7 days testing ( see EN 14509 clause B.3.4) is to be done. The reduction in tensile strength after ageing shall not exceed 15 % of the mean value of the tensile strength in ambient temperature<br><u>For all other panel type</u> the procedure in EN 14509 Annex B.2 is followed so that the panels are tested 14 days in the temperature as described in B.2.4. The reduction in tensile strength after ageing shall not exceed 17% of the mean value of the tensile strength in ambient temperature |
| Tolerances; damages evaluated by visual inspection                                                                                                                                                | If no serious damages or faults found; Panel can be reused<br>If serious damages are found causing weakness in strength, in insulation behavior or tightness of joints then those panels are rejected                                                                                                                                                                                                                                                                                                                                              |
| <b>Moisture content</b>                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| If no notable wetness of core material found the panels can be reused                                                                                                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |

### Tensile strength $f_{Ct}$

Characteristic value of tested values is determined according to EN 14509 A [9] as 16.3 for 30 tensile tests from Table 15:

$$n = 30$$

$$\text{Mean value of test results: } 0.092 \text{ N/mm}^2$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n L_n(x_i) = -2.431$$

$$\sigma_y = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (L_n(x_i) - \bar{y})^2} = 0.341$$

$$R_k = e^{\bar{y} - k \cdot \sigma_y}$$

$$k = 1.87$$

$$\underline{f_{Ct,Rk}} = 0.046 \text{ N/mm}^2$$

Minimum value for tensile strength  $f_{Ct}$  is according to type approval of that time  $0.150 \text{ N/mm}^2$ , thus the tested value would not meet the criteria  $f_{Ct,Rk} > 0.9 f_{Ct,Declared}$  and new declared values should be determined for the reused panel patch. On the other hand it should be noted that the original tensile test results were very low and 2018 tested values were almost 60% higher than those. Thus, it is difficult to draw conclusion on ageing behaviour based on these test series.

### Shear strength $f_{Cv}$

Characteristic value of tested values is determined according to EN 14509 A [9] as 16.3 for 3 shear tests from

Table 29:

$$\begin{aligned}
 n &= 3 \\
 \text{Mean value of test results: } &0.061 \text{ N/mm}^2 \\
 \bar{y} &= \frac{1}{n} \sum_{i=1}^n L_n(x_i) = -2.819 \\
 \sigma_y &= \sqrt{\frac{1}{n-1} \sum_{i=1}^n (L_n(x_i) - \bar{y})^2} = 0.227 \\
 R_k &= e^{\bar{y} - k \cdot \sigma_y} \\
 k &= 3.15 \\
 \underline{f_{Cv,Rk}} &= 0.029 \text{ N/mm}^2
 \end{aligned}$$

Minimum value for shear strength  $f_{Cv}$  is according to type approval of that time  $0.054 \text{ N/mm}^2$ , thus the tested value would not meet the criteria  $f_{Cv,Rk} > f_{Cv,Declared}$ . It should be noted, that number of test specimen was very low thus leading to very high  $k$ -value.

## Annex D Photographs



Figure 47 S-N4-SL3-1mmS350-1 test arrangement



Figure 48 S-N4-SL3-1mmS350-1 panel condition during the test.

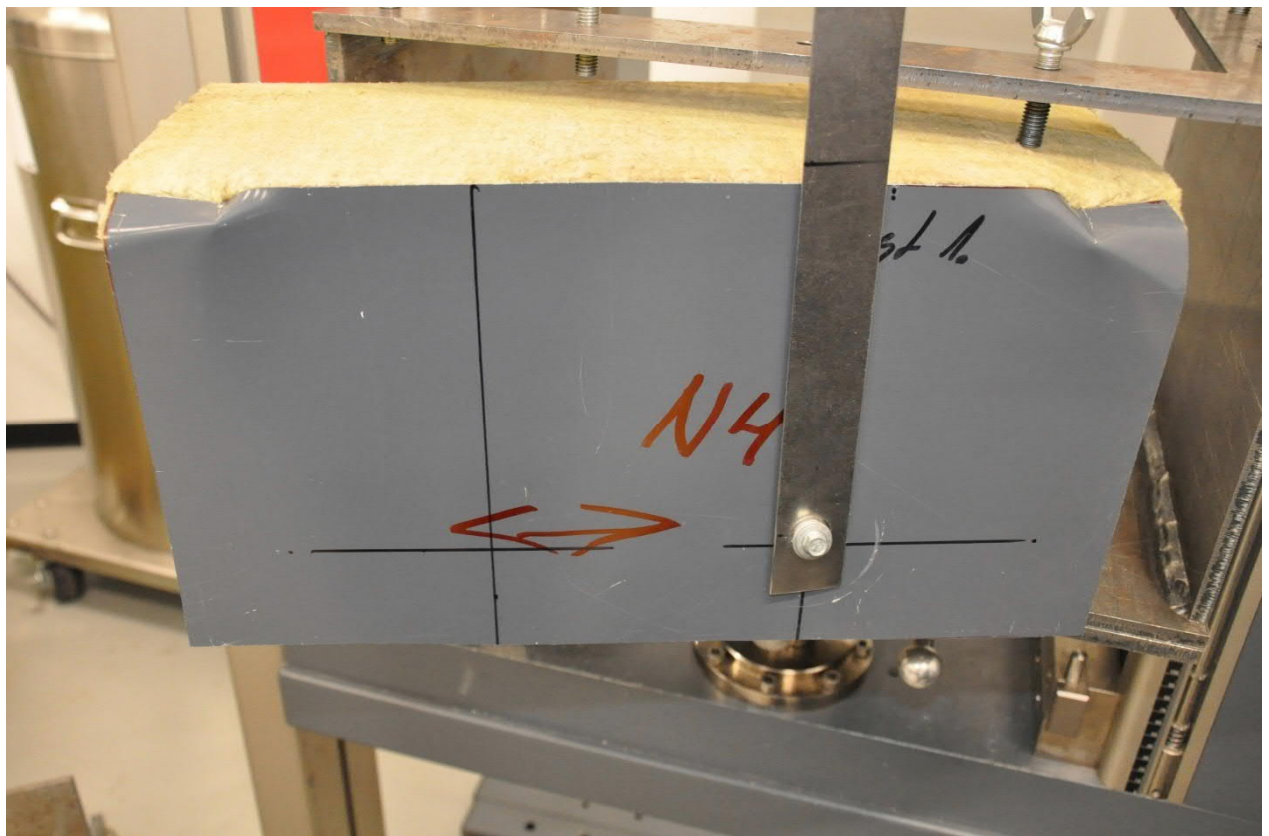
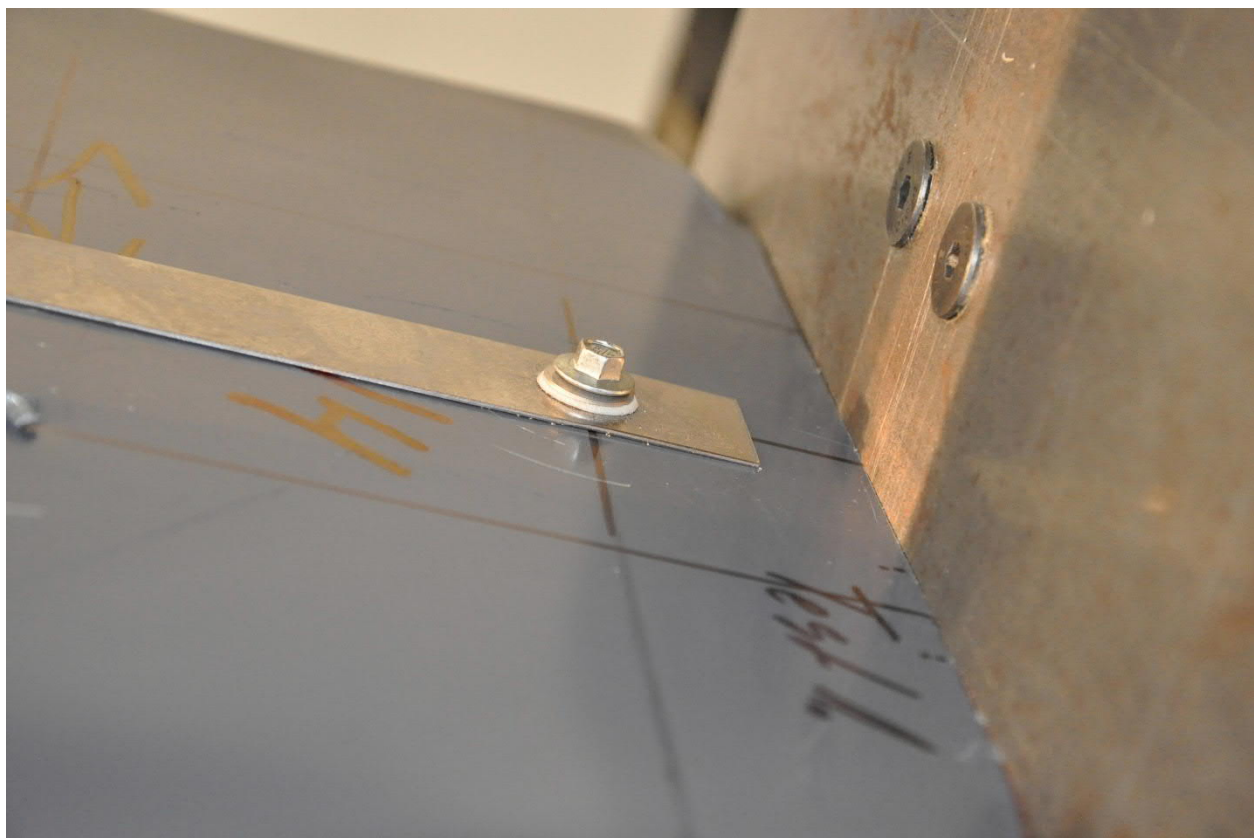


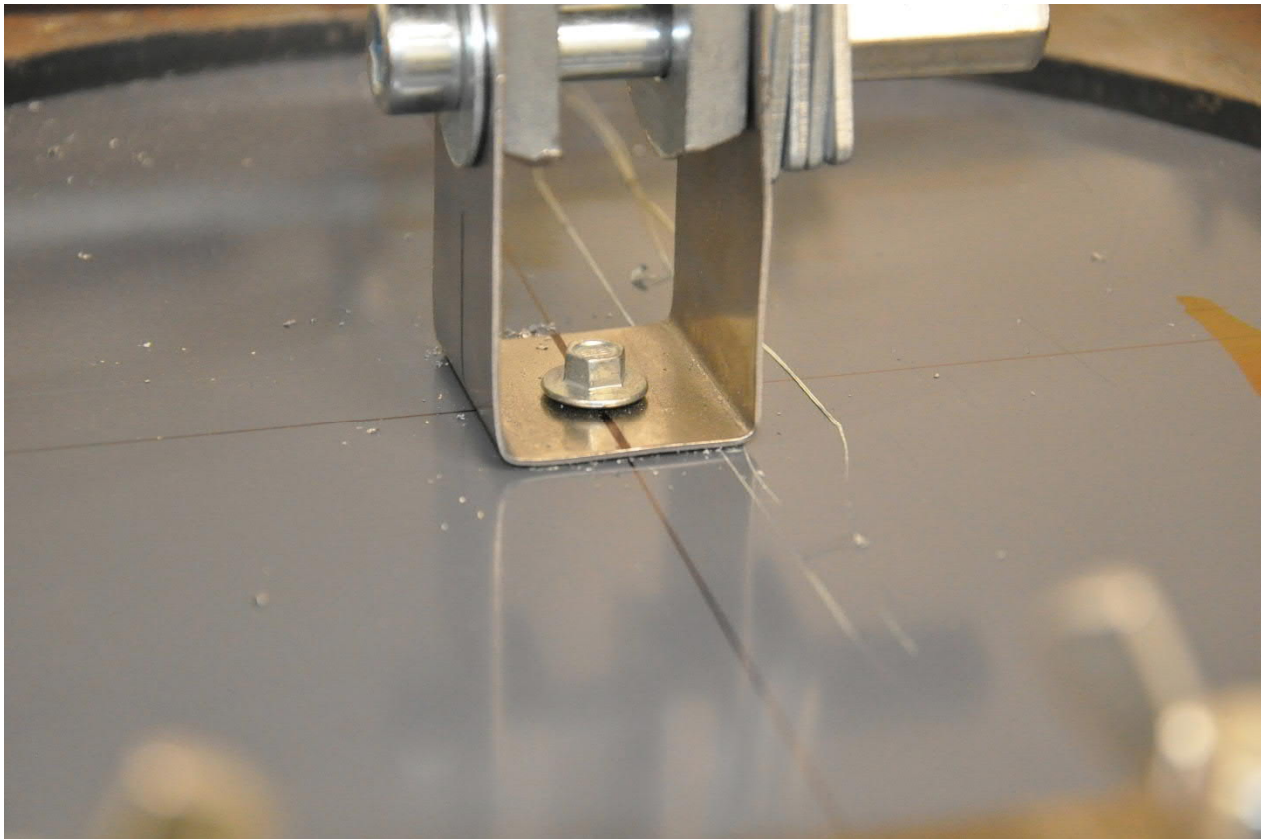
Figure 49 S-N4-SL3-1mmS350-1 panel condition after the test.



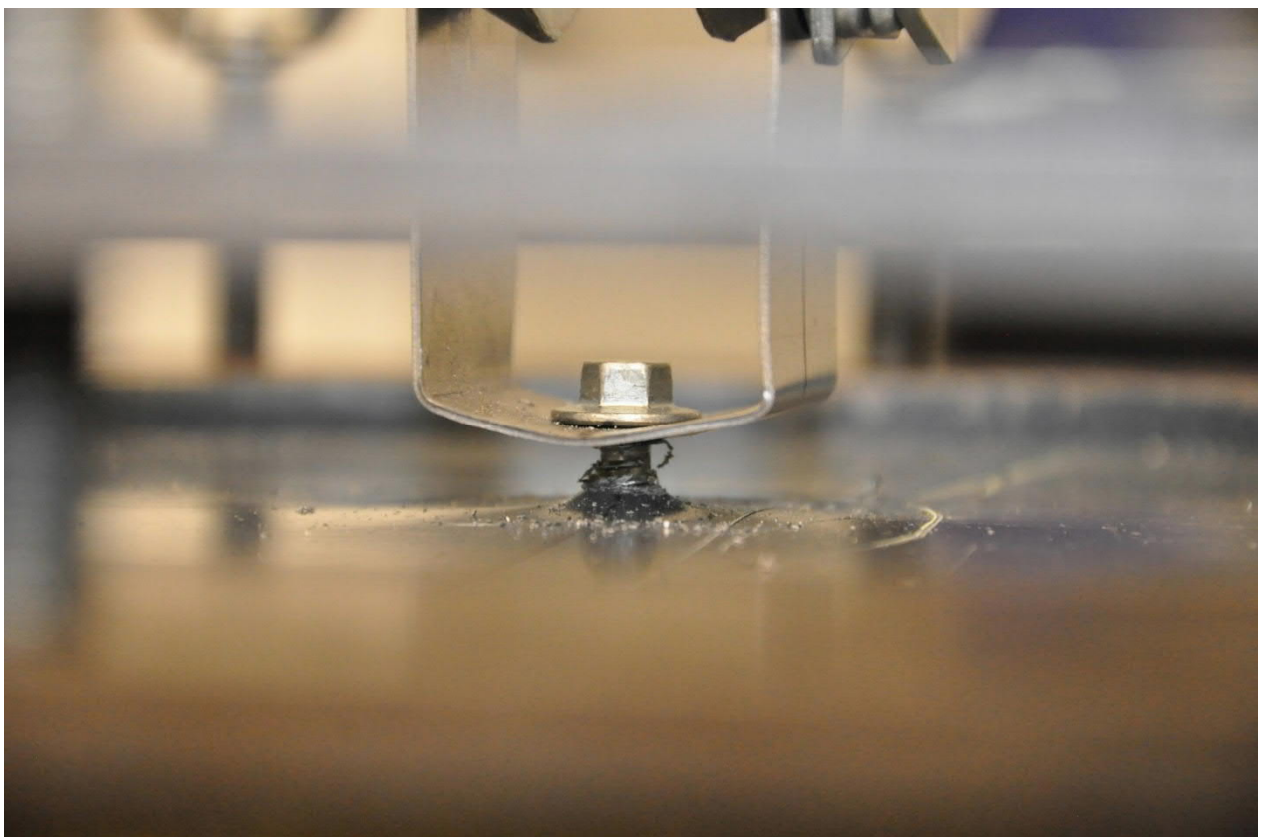
*Figure 50 S-N4-SL3-1mmS350-1-1 before the test.*



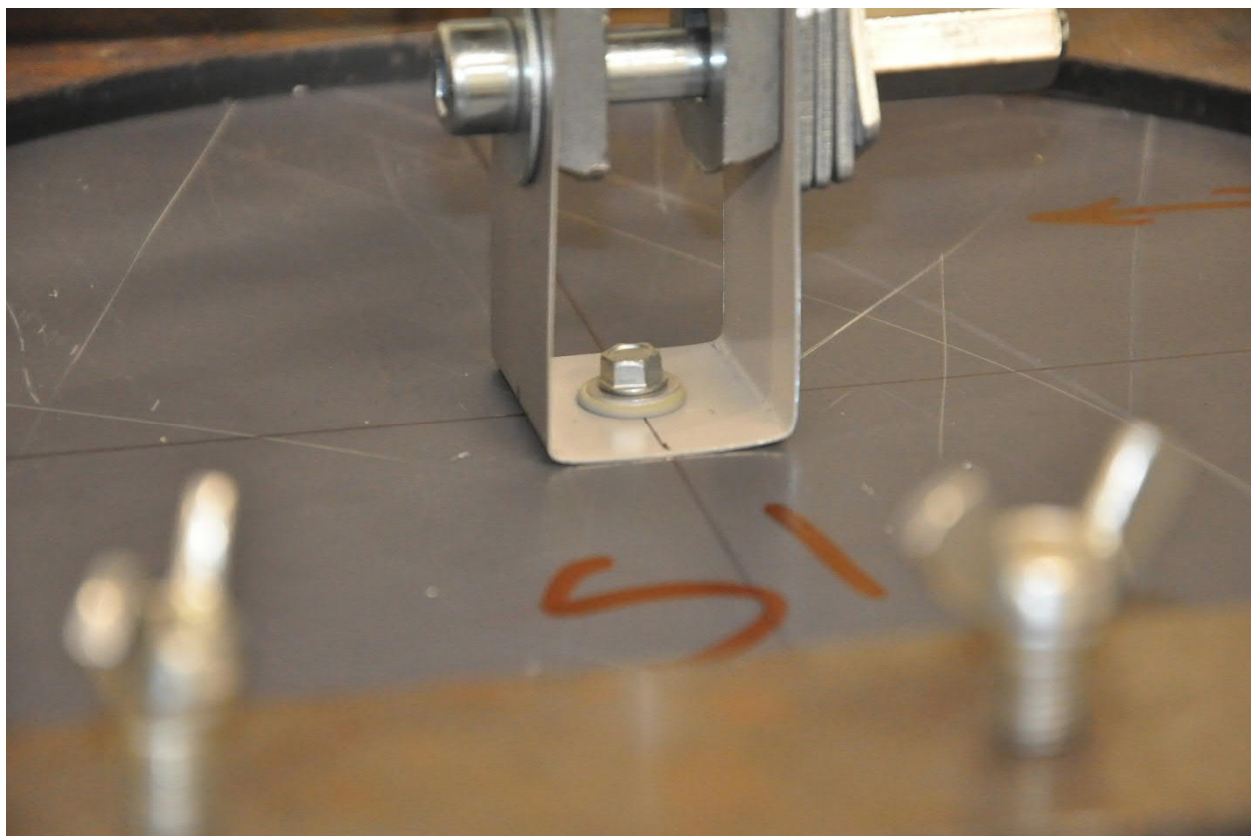
*Figure 51 SL3 screw pull-out failure mode in shear tests.*



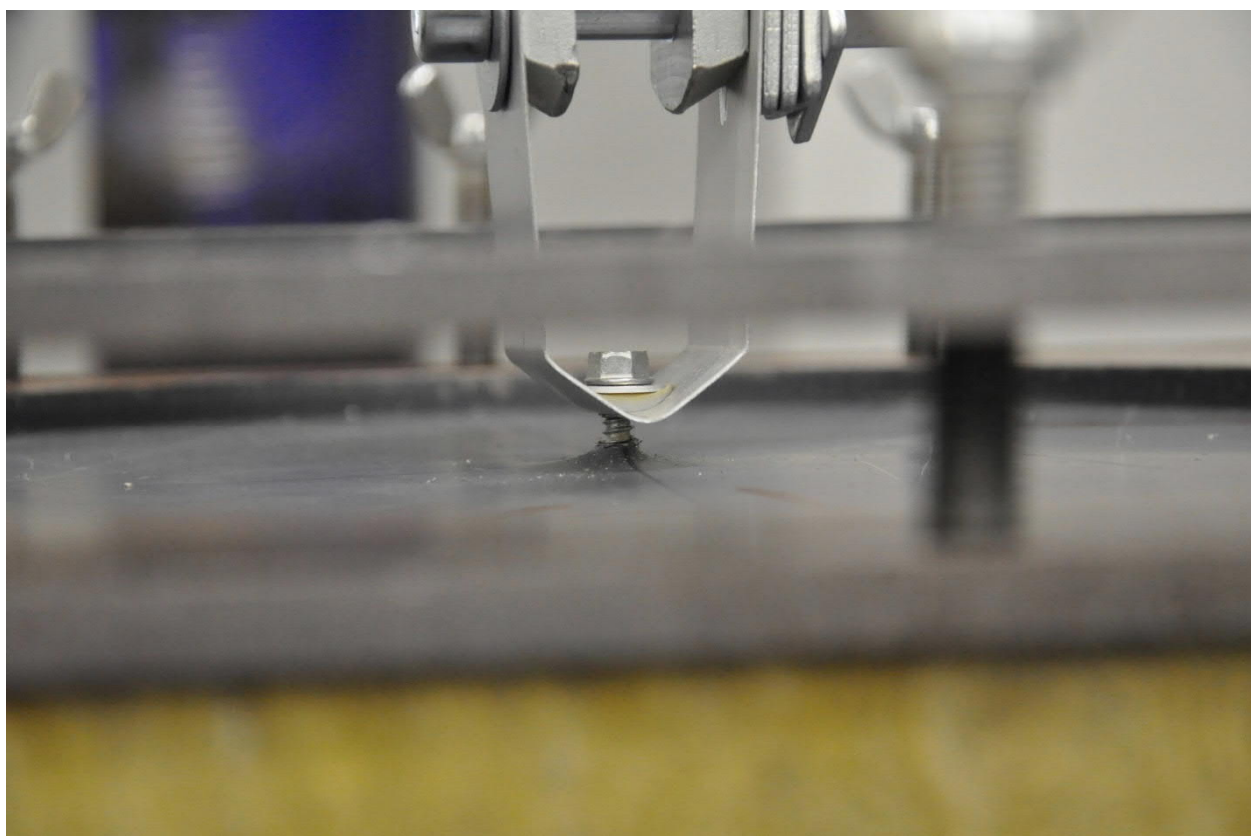
*Figure 52 T-N4-SL3-1mmS350-1 before the test.*



*Figure 53 SL3 failure mode in tensile tests.*



*Figure 54 T-S1-SL2-0,6mmS280-1 before the test.*



*Figure 55 SL2 failure mode in tensile tests.*



*Figure 56 Screws for tests.*