Structural Applications of Ferritic Stainless Steels (SAFSS)

Work package 3: Structural and thermal performance of steel-concrete composite floor systems

Task 3.2: Decking tests in the construction stage

Universitat Politècnica de Catalunya (UPC)

Departament d'Enginyeria de la Construcció
Departament de Resistència de Materials i Estructures a l’Enginyeria
Universitat Politècnica de Catalunya
**Project name:** Structural Applications of Ferritic Stainless Steels  
**Project's short name:** SAFSS

### Change log:

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Status (draft/proposal/updated/to be reviewed/approved)</th>
<th>Author(s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>17.11.11</td>
<td>Draft</td>
<td>Esther Real/Enrique Mirambell</td>
<td>After first tests</td>
</tr>
<tr>
<td>0.2</td>
<td>25.05.12</td>
<td>Draft</td>
<td>Esther Real/Itsaso Arrayago</td>
<td>After continuous tests</td>
</tr>
<tr>
<td>0.3</td>
<td>24.10.12</td>
<td>Draft</td>
<td>Esther Real/Itsaso Arrayago</td>
<td>After small scale tests</td>
</tr>
<tr>
<td>0.4</td>
<td>13.11.12</td>
<td>Final version</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EUROPEAN COMMISSION

Research Programme of
The Research Fund for Coal and Steel-Steel RTD

Title of Research Project: Structural Application of Ferritic Stainless Steels (SAFSS)

Executive Committee: TGS8

Contract: RFSR-CT-2010-00026

Commencement Date: July 01, 2011

Completion Date: June 30, 2013

Beneficiary: Universitat Politècnica de Catalunya (UPC)

Research Location: Universitat Politècnica de Catalunya
C/ Jordi Girona, 31
08034-Barcelona
España

Project leader: Esther Real

Report authors: Esther Real, Itsaso Arrayago, Enrique Mirambell, Frederic Marimon, Miquel Ferrer
# Contents

1. INTRODUCTION ......................................................... 5
   1.1 Objectives .................................................. 5
   1.2 Work programme and task distribution ................. 5
2. DEFINITIONS .......................................................... 6
   2.1 Geometrical definition .................................... 6
   2.2 Test definition .............................................. 6
       2.2.1 Simply supported decking tests ................. 6
       2.2.2 Continuous decking test ....................... 7
       2.2.3 Internal support test (Small scale moment rotation test) ....................... 8
       2.2.4 End support test (Small scale web crushing test) .......... 9
          2.2.5 Tensile test .................................... 9
3. TENSILE TEST RESULTS ............................................. 10
   3.1 Producer A ................................................... 9
   3.2 UPC ............................................................ 10
   3.3 SCI ............................................................. 11
4. ANALYSIS OF TENSILE TESTS ...................................... 11
   4.1 Cold-formed effects ...................................... 11
   4.2 Analytical expression ..................................... 12
5. EMBOSSEMENTS ......................................................... 12
6. POSITIVE BENDING MOMENT TEST RESULTS .................... 13
   6.1 Load-displacement curves ................................ 14
   6.2 Gauge results .............................................. 15
   6.3 Positive bending moment test figures ................. 16
7. ANALYSIS OF RESULTS FOR POSITIVE BENDING MOMENT TESTS 18
   7.1 Ultimate load predicted by EN 1993-1-3 ............... 18
   7.2 Elastic critical buckling stress analysis and comparison 19
   7.3 Comparison with similar test results ................ 21
   7.4 Numerical analysis ....................................... 22
8. NEGATIVE BENDING MOMENT TEST RESULTS ..................... 23
   8.1 Load-displacement curves ................................ 23
   8.2 Gauge results .............................................. 24
   8.3 Negative bending moment test figures ............... 26
9. ANALYSIS OF RESULTS FOR NEGATIVE BENDING MOMENT TESTS 27
   9.1 Ultimate load predicted by EN 1993-1-3 ............... 27
   9.2 Elastic critical buckling stress analysis and comparison 27
   9.3 Comparison with similar test results ............... 29
10. CROSS SECTIONAL STIFFNESS ANALYSIS ......................... 30
11. CONTINUOUS DECKING TEST RESULTS ......................... 31
   11.1 Load-displacement curves ................................ 31
   11.2 Middle support reaction evolution ................... 32
   11.3 Bending moment evolution ................................ 33
   11.4 Continuous decking test figures ..................... 34
12. ANALYSIS OF RESULTS FOR CONTINUOUS DECKING TESTS .... 36
   12.1 Comparison between double and simply supported tests 36
   12.2 Ultimate load predicted by EN 1993-1-3 ............... 36
   12.3 Preliminary FEM study ................................... 37
13. INTERNAL SUPPORT TEST RESULTS .............................. 37
   13.1 Load-displacement curves ................................ 39
   13.2 Internal support test figures ......................... 40
14. ANALYSIS OF RESULTS FOR INTERNAL SUPPORT TESTS ....... 41
14.1 Ultimate load predicted by EN 1993-1-3 41
14.2 Moment-Rotation diagrams 43
14.3 Comparison with similar test results 46
15. END SUPPORT TEST RESULTS 47
  15.1 Load-displacement curves 47
  15.2 End support test figures 48
16. ANALYSIS OF RESULTS FOR END SUPPORT TESTS 49
  16.1 Ultimate load predicted by EN 1993-1-3 49
  16.2 Comparison with similar test results 50
  16.3 Comparison between u=40mm and u=60mm tests 50
17. CONCLUSIONS 51
18. REFERENCES 51
1. INTRODUCTION

1.1 Objectives

The use of composite floor slabs is well established and the design approach is presented in Eurocode 4 EN 1994-1-1. However, there is an opportunity to promote the use of visually exposed composite slabs, as part of an energy saving strategy in which the thermal capacity of the floor slab is mobilised. The use of ferritic stainless steels is key to this strategy. Therefore, in order to develop this technology further, it is necessary to satisfy the required structural performance of composite slabs using profiled decking rolled from ferritic stainless strip steel. The scope of these tests is limited to a typical composite deck profile of approximately 60 mm depth that is currently rolled in galvanized steel strip. The information gained will demonstrate if ferritic stainless steels can be used in this application and what modifications, if any, are required for the design process in EN 1994-1-1 and EN 1994-1-2 (Fire).

1.2 Work programme and task distribution

Production feasibility for composite decking

The scope of work addresses the practicability of cold rolling a typical composite profile of 60 to 70 mm depth using ferritic stainless steel strip of 1 to 1.2 mm thickness. The cold rolling process will be assessed in terms of the adjustments necessary for this type of steel in comparison to galvanized steel strip of the same thickness. Problems will be identified and advice given on cold rolling of other generic profile shapes.

This work has been carried out in a manufacturer of strip steel and profiled decking. The details of the work depend on the precise manufacturing process, but the likely sequence is as follows:

- Replace a coil of strip steel by an equivalent ferritic stainless steel coil cut to the correct width.
- Use existing roll settings and rolling speed, and evaluate the conformity of the deck shape to tolerances etc.
- Modify the rolling procedure, if required, to achieve the correct tolerances.
- Carry out tensile tests on the ferritic stainless steel strip in comparison to the galvanized steel strip.
- Make recommendations for rolling of other deck profiles.

Decking tests in the construction stage (UPC)

Composite decking is designed primarily to support the weight of wet concrete and operatives during the construction process. The decking is normally placed over 2 or 3 spans so that it benefits from continuity, and spans of 3 to 3.6 m are achieved without temporary propping. This work will address the bending and crushing resistances of the deck profile rolled successfully in WP 3.1. The results are compared to the equivalent galvanized steel decking and also compared to design to EN 1993-1-3.
2. DEFINITIONS

2.1 Geometrical definition

A general view of the studied sheeting profile is presented in Figure 2.1.

![Figure 2.1. General geometrical definition of the whole cross section.](image)

Profile sheets provided from producer A:

- Geometry: a 58mm-high profile for whole WP3
- Grade: 1.4003-2B (CR & skin-passed) and 1.4621-BA (CR & bright annealed) Only 1.4003 for WP3.2, WP3.3
- Thickness: 0,80 mm

2.2 Test definition

Different decking tests are reported out in this study: simply supported decking tests subjected to positive and negative bending, continuous decking tests, small scale tests and tensile tests. Testing procedures were the ones described in EN 1993-1-3, Annex A. Test definitions are shown bellow.

2.2.1 Simply supported decking tests.

This test is necessary to determine the midspan moment resistance and the effective flexural stiffness.

*Positive bending moment tests (M+)*

Positive bending moment tests were carried out using simply supported stainless steel sheets. The tests were defined according to EN 1993-1-3, Annex A proposals shown on Figure 2.2. The total length of the sheet was 3100mm, corresponding 50mm to each
support section, as can be seen in Figure 2.3a. The sheet was subjected to a uniformly distributed load configuration, introduced by 4 longitudinally distributed loads. A total of three bending up tests were carried out in this study.

*Negative bending moment tests (M-)*

Negative bending moment tests were conducted using a similar test configuration, placing the sheet upside down. EN 1993-1-3 definition proposal and the final configurations are presented in Figure 2.2 and Figure 2.3b.

![Figure 2.2. EN 1993-1-3 proposal for bending test definition.](image)

![Figure 2.3a. Positive bending moment tests.](image)
2.2.2 Continuous decking test

This test may be used to determine the resistance of a sheet that is continuous over two or more spans to combinations of moment and shear internal supports, and its resistance to combined moment and support reactions for a given support width.

Three continuous decking tests on 2x3m spans were conducted in order to study bending-shear interaction in the middle support, so as to compare results with the ultimate bending moments obtained from previous single span tests. The EN 1993-1-3 proposals for continuous decking tests are gathered in Figure 2.4. The finally adopted test set-up is shown in Figure 2.5 and may be used to determine the resistance of a sheet that is continuous over two or more spans to combinations of moment and shear at internal supports, and its resistance to combined moment and support reaction for a given support width.
The loading should preferably be uniformly distributed (applied using an air bag or a vacuum chamber, for example). Alternatively any number of line loads (transverse to the span) may be used, arranged to produce internal moments and forces that are appropriate to represent the effects of uniformly distributed loading.

**2.2.3 Internal support test (Small scale moment rotation test)**

The internal support test is a small scale moment rotation tests to simulate negative bending behavior in the internal support and the influence of the support reaction (web crushing).

Different span lengths ($s=430\text{mm}$, $s=705\text{mm}$ and $s=1200\text{mm}$) have been tested to obtain a good characterization of the bending moment-reaction interaction but the total length of the sheet was $1300\text{mm}$ in all tests. Figure 2.6 shows the internal support test set up. The sheet was simply supported and subjected to a concentrated load in middle span section that was directly applied on the sheet to simulate the internal support effect of a continuous beam. A total of nine sheets were tested, three for each span length.
2.2.4 End support test (Small scale web crushing test)

Edge support reaction was tested by conducting four end support tests. The total sheet length was also 1300mm, but the load was applied in a bearing length of 300mm. Two tests had \( u = 40 \text{mm} \) while others had \( u = 60 \text{mm} \), in order to get the influence of the \( u \) distance. The test set up is shown in Figure 2.7.
2.2.5 Tensile test

Due to the non-linear stainless steel stress-strain curve it is necessary to also know the actual material behaviour to analyze tests results.

Tensile tests were carried out in different laboratories to establish the strength and the initial elastic modulus of the material.

3. TENSILE TEST RESULTS

Previous to the decking test it was necessary to characterise the stainless steel used in the fabrication. Some tensile tests were performed at LERMA laboratory (UPC), at SCI laboratory and at producer A laboratory in order to characterize the material. The coupons tested by producer A were extracted from the original plate before cold-forming and the coupons tested by UPC and SCI were extracted from the decks in the final cold-formed condition.

3.1 producer A

The tests carried out by producer A [3], were tested in three different directions; longitudinal, transverse and with a 45° angle. Table 3.1 and Figure 3.1 summarize the results.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Direction</th>
<th>Rp0,2% (Mpa)</th>
<th>Rp1% (Mpa)</th>
<th>Rm (Mpa)</th>
<th>A (%)</th>
<th>Ag (%)</th>
<th>E (Gpa)</th>
<th>n</th>
<th>r</th>
<th>Ep (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>948368B</td>
<td>ST</td>
<td>322,9</td>
<td>348,8</td>
<td>503,6</td>
<td>27,2</td>
<td>17,6</td>
<td>225</td>
<td>0,221</td>
<td>0,778</td>
<td>0,81</td>
</tr>
<tr>
<td>948368B</td>
<td>ST</td>
<td>324,1</td>
<td>351,2</td>
<td>503,2</td>
<td>27,6</td>
<td>17,5</td>
<td>190</td>
<td>0,219</td>
<td>0,765</td>
<td>0,81</td>
</tr>
<tr>
<td>948368B</td>
<td>SL</td>
<td>304,8</td>
<td>334,8</td>
<td>491,6</td>
<td>28,8</td>
<td>18,1</td>
<td>169</td>
<td>0,226</td>
<td>0,624</td>
<td>0,81</td>
</tr>
<tr>
<td>948368B</td>
<td>SL</td>
<td>304,6</td>
<td>334,0</td>
<td>490,9</td>
<td>28,7</td>
<td>18,1</td>
<td>175</td>
<td>0,226</td>
<td>0,630</td>
<td>0,81</td>
</tr>
<tr>
<td>948368B</td>
<td>45°</td>
<td>306,5</td>
<td>331,2</td>
<td>479,0</td>
<td>30,4</td>
<td>19,0</td>
<td>173</td>
<td>0,225</td>
<td>0,949</td>
<td>0,81</td>
</tr>
<tr>
<td>948368B</td>
<td>45°</td>
<td>304,7</td>
<td>328,1</td>
<td>475,4</td>
<td>31,1</td>
<td>19,1</td>
<td>173</td>
<td>0,225</td>
<td>0,981</td>
<td>0,81</td>
</tr>
</tbody>
</table>

Table 3.1 Table summarizing the results of the tensile test performed by producer A.
Figure 3.1 Stress-strain curves of the tensile test performed by producer A.

3.2 UPC

The other tests, carried out at LERMA laboratory (UPC), were done only in longitudinal direction because it was the only way to obtain a standardized coupon from the cold-formed sheets. Four tests were performed and the results are shown in Table 3.2 and figure 3.2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen</th>
<th>b (mm)</th>
<th>t (mm)</th>
<th>Zn (mm)</th>
<th>L₀</th>
<th>L (%)</th>
<th>Fu (N)</th>
<th>Fy (0.2%) (N)</th>
<th>fₓ (N/mm²)</th>
<th>fy (0.2%) (N/mm²)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FSS_Sheet</td>
<td>15.98</td>
<td>0.83</td>
<td>0.00</td>
<td>50</td>
<td>63</td>
<td>6371</td>
<td>4492</td>
<td>480</td>
<td>339</td>
<td>28-6-11</td>
</tr>
<tr>
<td>2</td>
<td>FSS_Sheet</td>
<td>16.12</td>
<td>0.81</td>
<td>0.00</td>
<td>50</td>
<td>64</td>
<td>6426</td>
<td>4185</td>
<td>492</td>
<td>321</td>
<td>28-6-11</td>
</tr>
<tr>
<td>3</td>
<td>FSS_Sheet</td>
<td>16.08</td>
<td>0.84</td>
<td>0.00</td>
<td>50</td>
<td>64</td>
<td>6478</td>
<td>4378</td>
<td>480</td>
<td>324</td>
<td>28-6-11</td>
</tr>
</tbody>
</table>

Table 3.2 Table summarizing the results of the tensile test performed at UPC.
3.3 SCI

Similar tensile tests have been done in the SCI laboratory for the same material. Those tests were conducted in cold formed material, as the ones provided by LERMA. Some of the test result and the most important material-parameters are presented in Figure 3.3 and Table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>218104 MPa</td>
</tr>
<tr>
<td>$\sigma_{0.2}$</td>
<td>320 MPa</td>
</tr>
<tr>
<td>$\sigma_u$</td>
<td>488 MPa</td>
</tr>
<tr>
<td>$\varepsilon_u$</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 3.3 Table summarizing the results of the tensile test performed at SCI.

4. ANALYSIS OF TENSILE TESTS

In this section, tensile test results are analyzed. The effects of the cold-formed process and the analytical expression, found for the material, are shown below.

4.1 Cold-formed effects

The comparison between the tensile test results provided by producer A (performed in virgin material) and the ones tested in LERMA (after the material has been cold-
formed) allows determining the effect of the cold-forming process in ferritic stainless steel.

As it is shown in Figure 4.1, the cold-forming process increases the ultimate resistance, while the behaviour in low levels of deformation remains the same.

![Figure 4.1 Cold-formed effect](image)

4.2 Analytical expression

The analytical expression describing the material’s behaviour used for the numerical simulation is presented in Equation 4.1. The values for cold-formed material, from UPC and SCI, have been chosen and presented in Table 4.1.

\[
\varepsilon = \begin{cases} 
\frac{\sigma}{218104} + 0.002\left(\frac{\sigma}{320}\right)^{12} & \text{for } \sigma \leq 320\text{MPa} \\
\frac{\sigma - 320}{12565,19} + 0.093\left(\frac{\sigma - 320}{488 - 320}\right)^{1.5} + 0.0035379 & \text{for } \sigma > 320\text{MPa}
\end{cases} 
\]  

(eq. 4.1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>218104 MPa</td>
</tr>
<tr>
<td>(\sigma_{0.2})</td>
<td>320 MPa</td>
</tr>
<tr>
<td>n</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 4.1 Material parameters from tensile tests.

5. EMBOSSMENTS

Before performing the tests, a geometrical control of the delivered material was done. It was warned that the embossments were shorter than expected they should. The nominal values should be \(E=3\) mm \(F'=10\) mm (see Fig. 5.1) but in some cases the measurements were different (Fig. 5.2).
After measuring some of the embossments for different rows of the deck profiles and making a statistical evaluation, the calculated average value of the embossment depth was 2,4mm instead of 3,0mm.

![Figure 5.1](image1.png)

![Figure 5.2](image2.png)

After this result the decision was to test decking profiles, because the embossments do not affect significantly the results, but getting new profiles for composite slabs.

### 6. POSITIVE BENDING MOMENT TEST RESULTS

The results for the three positive bending moment tests are summarized in this section.

These results are presented as load-displacement curves (Figure 6.2) and a Table 6.1, summarizing the ultimate loads and displacements for each test. The displacements were measured in the middle span section of the deck. The weight of the loading upper structure should be added to the load values obtained from load cell. The loading settings are 900N in weight.

Two load-displacement curves were obtained in each test, with two linear displacement transducers measuring linear displacement of the sheet along the vertical axis in the middle span section, as shown in figure 6.1.
In all the tests spreading of corrugations was prevent by using transverse ties under the loading sections. Load was applied by steel cross beams arranged to approximate uniformly distributed loading (see section 6.3).

In simply supported tests the boundary conditions were with one bearing support with free rotation and free longitudinal displacement and the other one only with free rotation. Decks were connected to the supports (see section 6.3).

Bearing support sections were stiffened by using rectangular hollow sections and timber pieces.

6.1 Load-displacement curves

Even if two curves were obtained for each test, a single curve is presented for simplicity. This single curve has been calculated as an average curve. All experimental curves are also presented in Annex A.
When in test n°2 a load of 11.48kN was reached the sheet started buckling. This phenomenon is appreciated in the load-displacement curve presented in Annex A and it can be also seen on the strain gauges behaviour shown later.

Considering the load distribution in positive bending moment test set up, the maximum moment can be obtained applying statics:

\[
R_A = R_B = 2P \quad \text{(eq. 6.1)}
\]

\[
M_{max} = -0.375 \cdot P - 1.125 \cdot P + 2P \cdot 1.500 = 1.500 \cdot P \quad \text{(eq. 6.2)}
\]

where \( P = Q/4 \) \( \rightarrow \) \( M_{max} = 0.375 \cdot Q \quad \text{(eq. 6.3)}\)
The maximum bending moments can be calculated and presented in Table 6.2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Ultimate positive bending moment (kN·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test nº1</td>
<td>5,37</td>
</tr>
<tr>
<td>Test nº2</td>
<td>5,82</td>
</tr>
<tr>
<td>Test nº3</td>
<td>5,93</td>
</tr>
<tr>
<td>Mean</td>
<td>5,71</td>
</tr>
</tbody>
</table>

Table 6.2 Maximum positive bending moments

6.2 Gauge results

During the second positive bending moment test (named as test nº2) several points of the sheet were monitored in order to obtain the strain deformation in different points. From these gauge results some conclusions can be drawn.

The gauge distribution along the cross section is shown in Figures 6.4, 6.5 and 6.6.

Figure 6.4. Wave labelling along the cross section.

Figure 6.5. Gauge labelling and distribution in waves 1 and 5, respectively.
Defo

defo

obta

All th

Gau

Gloa

sho

Figure 6.6. Gauge labelling and distribution in wave 3.

Deformation measures in both top and bottom fibres allow determining the membrane deformation in the sheet, defining the strain distribution in the cross section and obtaining the deformed planes.

All the experimental load-strain curves are plotted in Annex B.

Gauge load-deformation curve comparison

Load-deformation curves are compared herein for the gauges that are supposed to show a similar behaviour. The compared gauges are the ones situated in the compressed fiber, in order to when the critical buckling load is reached. Analyzing Figure 6.7, the behaviour of the three points is very similar until a load of 11.48kN is reached: At this point curves diverge and buckling occurs for a deformation close to 0,058%.

Figure 6.7. Comparison between membrane deformations for gauges 8/23, 9/24 and 10/25.

6.3 Positive bending moment test figures

This section shows a selection of figures during the bending up tests, reflecting the most characteristic aspects of these tests.
Figure 6.8. General view of positive bending moment test configuration before and after collapse.

Figure 6.9. Details of the displacement transducer positioning and support conditions.

Figure 6.10. Detail of the load introduction mechanism and buckled zone.
More pictures are presented in Annex C.

7. ANALYSIS OF RESULTS FOR POSITIVE BENDING MOMENT TESTS

7.1 Ultimate load predicted by EN 1993-1-3

According to EN 1993-1-3 section 6.1 Resistance of cross-sections and section 6.1.4 Bending Moment, the design resistance for bending about one principal axis of a cross-section is determined as follows:

-if the effective section modulus $W_{\text{eff}}$ is less than the gross elastic section modulus $W_{\text{el}}$.

$$M_{c,Rd} = \frac{W_{\text{eff}} \cdot f_{yb}}{\gamma_{M0}}$$  \hspace{1cm} (eq. 7.1)

-if the effective section modulus $W_{\text{eff}}$ is equal to the gross elastic section modulus $W_{\text{el}}$ but no more than $W_{pl} / \gamma_{M0}$.

$$M_{c,Rd} = f_{yb} \cdot (W_{el} + (W_{pl} - W_{el})4(1 - \frac{\lambda_{e,\text{max}}}{\lambda_{e,0}})) / \gamma_{M0}$$  \hspace{1cm} (eq. 7.2)

Where $\lambda_{e,\text{max}}$ is the slenderness of the element which correspond to the largest value of $\frac{\lambda_{e}}{\lambda_{e,0}}$.

$W_{\text{eff}}$ needs to be calculated considering the compressed area in positive and negative bending moment tests.

For the positive bending position test, the effective section modulus and the elastic section modulus values are:

$$W_{\text{el}}(\text{upper}) = 26,13 \text{cm}^3$$

$$W_{\text{eff}}(M+) = 15,63 \text{cm}^3$$

The maximum predicted value of the loading applied to the specimen for the positive bending position can be calculated using (eq. 7.1) and (eq.6.3) as:
\[ Q_{\text{max}} = \frac{M_{\text{max}}}{0.375} = \frac{W_{\text{eff}} f_y}{0.375 \gamma_{M0}} \]

\[ Q = 13.33 \text{kN} \quad \text{(eq. 7.3)} \]

Table 7.1 compares values of experimental and predicted ultimate loads in positive bending moment.

<table>
<thead>
<tr>
<th>Experimental ultimate load (kN)</th>
<th>EN 1993-1-3 predicted ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>14.34</td>
</tr>
<tr>
<td>Test n°2</td>
<td>15.52</td>
</tr>
<tr>
<td>Test n°3</td>
<td>15.82</td>
</tr>
<tr>
<td>Mean</td>
<td>15.23</td>
</tr>
<tr>
<td></td>
<td>13.33</td>
</tr>
</tbody>
</table>

Table 7.1 Comparison between experimental and predicted loads for positive bending moment tests.

7.2 Elastic critical buckling stress analysis and comparison

The elastic critical buckling stress can be obtained from different methodologies. Some of them are used herein and a comparison of the obtained values is also done.

a) Considering a linear elastic analysis of the test configuration, the value of the bending moment when buckling occurs can be obtained from the total applied load \(Q=4\cdot P\) and determine the stress when the elastic critical buckling load is reached (obtained from 6.2) for an elastic approximation:

\[ Q = 11.45 \text{kN} \quad M = 0.375 \cdot Q = 4.31 \text{kNm} \]

\[ \sigma = \frac{M}{W_{\text{el}}} \quad \text{(eq. 7.7)} \]

\[ \sigma_{\text{cr}} = 164.7 \text{ N/mm}^2 \]

b) Considering the stress calculated with the stress-strain equation (eq. 4.1) associated to strain gauge deformation when elastic buckling occurs:

\[ \sigma_{\text{cr}} = 124.8 \text{ N/mm}^2 \]

c) EN 1993-1-3 Section 6.2 *Buckling resistance* [2], refers to Section 5.5 when dealing with the effects of local and distortional buckling. In this section simplified procedures are recommended depending on the case.

The guidelines for this case of study are shown in Section 5.5.3 *Plane elements with edge or intermediate stiffeners*, and in particular Section 5.5.3.4 *Trapezoidal sheeting profiles with intermediate stiffeners*.

According to the mentioned standards, when having flanges with intermediate stiffeners subject to uniform compression, the effective cross-section of a flange with intermediate stiffeners should be assumed to consist of the reduced effective areas \(A_{s,\text{red}}\) including two strips of width \(0.5b_{\text{eff}}\) (or 15t), shown in figure 7.2, adjacent to the stiffener.
Once $A_s$ and $I_s$ are obtained, as shown above, the elastic critical buckling stress $\sigma_{cr,s}$ can be also obtained from one of the expressions detailed below:

For two symmetrically placed flange stiffeners ($M^*$), $\sigma_{cr,s}$ should be obtained from:

$$\sigma_{cr,s} = \frac{4,2 \cdot k_w \cdot E}{A_s} \sqrt[3]{\frac{I_s \cdot t^3}{8 \cdot b_e^2 \cdot (3b_e - 4b_1)}}$$

(eq. 7.8)

with:

$$b_e = 2b_{p,1} + b_{p,2} + 2b_s$$

(eq. 7.9)

$$b_1 = b_{p,1} + 0,5b_s$$

(eq. 7.10)

where:

- $b_{p,1}$ is the notional flat width of an outer plane element, as shown in figure 7.2;
- $b_{p,2}$ is the notional flat width of the central plane element, as shown in figure 7.2;
- $b_s$ is the overall width of a stiffener;
- $A_s$, $I_s$ are the cross-section area and the second moment of area of the stiffener cross-section according to figure 7.2.
- $k_w$ is a coefficient that allows for partial rotational restraint of the stiffened flange by the webs or other adjacent elements.

The values of $l_b$ and $k_w$ may be determined from the following:

$$l_b = 3,65 \cdot \sqrt[3]{\frac{I_s \cdot b_e^2 (3b_e - 4b_1)}{t^3}}$$

(eq. 7.11)
\[ k_{w0} = \sqrt{\frac{(2b_c + s_w) \cdot (3b_c - 4b_i)}{b_i (4b_c - 6b_i) + s_w (3b_c - 4b_i)}} \]  

(eq. 7.12)

Following this guideline the elastic critical buckling stress for the stiffeners \( \sigma_{cr,s} \) can be predicted:

\[ \sigma_{cr} = 130.17 \text{N/mm}^2 \]

Then the critical elastic buckling stress for the stiffener in the upper flange, calculated by EN 1993-1-3 is very similar to the one obtained experimentally from gauges information.

7.3 Comparison with similar test results

Results obtained in the tests performed in UPC can be compared to the ones published by the Universität Karlsruhe [4]. Those tests were also conducted in Cofraplus60 carbon steel sheets subjected to positive bending, negative bending and continuous beams and for small scale sheets.

The geometries used in this previous tests, so as tests configuration for bending tests are the similar to the ones used in this study, except the sheet thickness: while the previous tests sheets where 0,75mm thick, the ones conducted in the present campaign are 0,8mm.

Figure 7.3 show all the load-displacement curves are very similar one to each other, reaching similar ultimate loads being higher the loads in the UPC tests because the considered sheet thickness is slightly higher. These ultimate loads are presented in Table 7.2.

![Figure 7.3. Comparison of UPC results with previous ones for bending up tests.](image)

<table>
<thead>
<tr>
<th>UPC tests</th>
<th>Previous tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_u ) (kN)</td>
<td>( P_u ) (kN)</td>
</tr>
<tr>
<td>Test n°1</td>
<td>14,34</td>
</tr>
<tr>
<td>Test n°2</td>
<td>15,52</td>
</tr>
<tr>
<td>Test n°3</td>
<td>15,82</td>
</tr>
<tr>
<td>Mean</td>
<td>15,23</td>
</tr>
</tbody>
</table>

Table 7.2. Comparison of UPC results with previous ones for bending up tests.
A summary of the ultimate loads and corresponding ultimate bending moments is presented in Table 7.3.

<table>
<thead>
<tr>
<th>Ultimate load (kN)</th>
<th>Experimental</th>
<th>Previous test</th>
<th>EN 1993-1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14,34</td>
<td>14,46</td>
<td>13.33</td>
</tr>
<tr>
<td></td>
<td>15,52</td>
<td>13,93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15,82</td>
<td>13,90</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate positive bending moment (kN)</th>
<th>Experimental</th>
<th>Previous test</th>
<th>EN 1993-1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.37</td>
<td>5.42</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>5.82</td>
<td>5.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.93</td>
<td>5.21</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.71</td>
<td>5.29</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 7.3. Summary of results for positive bending moment.

7.4 Numerical analysis

A numerical study has been also conducted using Abaqus/CAE. In this analysis S4R shell elements have been used with a GMNIA analysis. The numerical model uses the experimental stress-strain data and the initial imperfections were calculated by a buckling analysis before the geometrical and material nonlinear analysis.

A good agreement between experimental and numerical load-deflection curves is shown in Figure 7.4.
Figure 7.4. Experimental and FEM results for positive bending moment test configuration.

Figure 7.5 presents a view of the final deformation obtained with the numerical model.

Figure 7.5 Final deformation obtained with the numerical model.
8. NEGATIVE BENDING MOMENT TEST RESULTS

The results of the three negative bending moment test results are summarized in this section. Load bearings, boundary conditions and measurements were similar to the ones used for the positive bending moment tests.

These results are presented as ultimate loads and displacements for each of the tests (Table 8.1) and load-displacement curves. The displacements were measured in the middle span section of the sheet. The loading settings are 1050N in weight.

8.1 Load-displacement curves

<table>
<thead>
<tr>
<th>Test</th>
<th>Ultimate load (kN)</th>
<th>Averaged displacement for the ultimate load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load-cell value + settings weight</td>
<td>Displacement due to load-cell value (setting weight effect not included)</td>
</tr>
<tr>
<td>Test n°1</td>
<td>16.44</td>
<td>54.17</td>
</tr>
<tr>
<td>Test n°2</td>
<td>15.29</td>
<td>53.23</td>
</tr>
<tr>
<td>Test n°3</td>
<td>15.75</td>
<td>53.07</td>
</tr>
</tbody>
</table>

Table 8.1. Achieved ultimate loads and displacements.

Figure 8.1. Load-displacement curves for negative bending moment tests.
When in test nº3 a load of 15.75kN was reached the sheet started buckling. This phenomenon is appreciated on the strain gauges behaviour shown later.

The maximum bending moments can be calculated and presented in Table 8.2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Ultimate negative bending moment (kN·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test nº1</td>
<td>6.17</td>
</tr>
<tr>
<td>Test nº2</td>
<td>5.73</td>
</tr>
<tr>
<td>Test nº3</td>
<td>5.91</td>
</tr>
<tr>
<td>Mean</td>
<td>5.94</td>
</tr>
</tbody>
</table>

Table 8.2 Maximum negative bending moments

8.2 Gauge results

During the third negative bending moment test (named as test nº3) several points of the sheet were monitorized in order to obtain the deformation on each point. From these gauge results, some conclusions can be drawn.

The gauge distribution along the cross section is shown in Figures 8.2, 8.3 and 8.4.

Figure 8.2. Wave labelling in cross section.

Figure 8.3. Gauge labelling and distribution in waves 1 and 5 respectively.

Figure 8.4. Gauge labelling and distribution in wave 3.
Deformation measures in both top and bottom fibres allow determining the membrane deformation in the sheet, defining the strain distribution of the cross section and obtaining the deformed planes.

**Gauge load-deformation curve comparison**

The load-membrane strain curves of the third test in the negative bending position were also divided in two groups, the ones that measured the compressed area of the section (G2/9 and G6/13) and the ones that measured the tensioned area (G3/10, G4/11 and G5/12).

The comparison between the load-membrane strain curves group that measured the compressed area and the ones that measured the tensioned area are shown below in figures 8.5 and figure 8.6 respectively.

![Figure 8.5 Load-membrane strain plot comparison between G2/9 and G6/13.](image)

As seen in figure 8.5, the behaviour of the two gauges on the compressed zone is similar until the applied load reaches the maximum load 15.75kN.

![Figure 8.6. Load-membrane strain plot comparison between G3/10, G4/11 and G5/12.](image)

8.3 **Negative bending moment test figures**
This section shows a selection of figures during the negative bending moment tests, reflecting the most characteristic aspects of these tests. Annex C gathers all the negative bending moment test figures.

![General test configuration](image)

**Figure 8.7. General test configuration.**

![Deformed shape after buckling occurs and detail from the support section](image)

**Figure 8.8. Deformed shape after buckling occurs and detail from the support section.**

### 9. ANALYSIS OF RESULTS FOR NEGATIVE BENDING MOMENT TESTS

#### 9.1 Ultimate load predicted by EN 1993-1-3

Applying the same expression used in the positive bending moment ultimate load calculation, but considering that

$$ W_{\text{eff}} (M-) = 17,43 \text{ cm}^3 $$

(eq. 9.1)

The maximum predicted value of the loading applied to the specimen for the negative bending position test is:

$$ Q_{\text{max}} = \frac{M_{\text{max}}}{0.375} = \frac{W_{\text{eff}} f_y}{0.375 \gamma_{M0}} \rightarrow Q = 14,87 \text{ kN} $$

(eq. 9.2)

Table 9.1 compares values of experimental and predicted for the ultimate loads in bending down tests.
<table>
<thead>
<tr>
<th>Experimental ultimate load (kN)</th>
<th>EN 1993-1-3 predicted ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>16.44</td>
</tr>
<tr>
<td>Test n°2</td>
<td>15.29</td>
</tr>
<tr>
<td>Test n°3</td>
<td>15.75</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>15.83</td>
</tr>
</tbody>
</table>

Table 9.1 Comparison between experimental and predicted loads for negative bending moment tests.

9.2 Elastic critical buckling stress analysis and comparison

The same elastic critical buckling stresses as in positive bending moment have been considered in this comparison, and the followed methodology has also been the same.

a) Linear elastic analysis when buckling occurs at the maximum load in test 3.

\[ \sigma = \frac{M}{W_{el}} \]  
\[ W_{el} \text{ (lower)} = 19.45 \text{ cm}^3 \]  
\[ \sigma_{cr} = 303.6 \text{ N/mm}^2 \] (eq. 9.3)

(b) Considering gauge deformation when elastic buckling occurs:

\[ \sigma_{cr} = 300.1 \text{ N/mm}^2 \]

c) EN 1993-1-3 [2] provides expressions for the determination of the critical stresses for cold-formed elements with trapezoidal shape and intermediate stiffeners in section 5.5.3.4. Considering that in the bending down test configuration cross section’s compressed zone has a single stiffener:

\[ \sigma_{cr,s} = \frac{4.2 \cdot k_w \cdot E}{A_s} \sqrt{\frac{I_s}{4 \cdot b_p^2 \cdot (2b_p + 3b_s)}} \] (eq. 9.5)

where:

- \( b_p \) is the notional flat width of plane element shown in figure 4.2;
- \( b_s \) is the stiffener width, measured around the perimeter of the stiffener, see figure 7.2;

The value of \( k_w \) may be calculated from the compression flange buckling wavelength \( l_b \) as follows:

If \( l_b/s_w \geq 2 \):
\[ k_w = k_{w0} \] (eq. 9.6)

If \( l_b/s_w < 2 \)
\[ k_w = k_{w0} - (k_{w0} - 1) \left[ \frac{2l_b}{s_w} - \left( \frac{l_b}{s_w} \right)^2 \right] \quad \text{(eq. 9.7)} \]

where:
\[ s_w \text{ is the slant height of the web.} \]

The values of \( l_b \) and \( k_{w0} \) may be determined from the following:

\[ l_b = 3,07 \times \sqrt{I_x} \times b_p^2 (2b_p + 3b_s) / t^3 \quad \text{(eq. 9.8)} \]

\[ k_{w0} = \sqrt{\frac{s_w + 2b_d}{s_w + 0,5b_d}} \quad \text{(eq. 9.9)} \]

with:
\[ b_d = 2b_p + b_s \quad \text{(eq. 9.10)} \]

Following this guideline the elastic critical buckling stress for the stiffener \( \sigma_{cr,s} \) can be predicted:

\[ \sigma_{cr,s} = 307.94 \text{ N/mm}^2 \]

9.3 Comparison with similar test results

Results obtained in the UPC experimental campaign can be compared to the ones published by the Universität Karlsruhe [4]. Those tests were also conducted in Cofrplus60 carbon steel sheets subjected to positive bending, negative bending moment.

The geometries used in this previous tests, so as tests configuration for bending tests are the same used in this study, except the sheet thickness: while the previous tests sheets where 0,75mm thick, the ones conducted in the present campaign are 0,8mm.

Figure 9.2 show all the load-displacement curves:
For negative bending moment tests, the ultimate load values are different for both tests campaigns. It is important to note that the cross section tested in Universität Karlsruhe was shorter than the one used in this study, involving just 4 waves instead of the original 5, as it can be seen bellow:

![Graph showing comparison of UPC results with previous ones for M-](image)

**Figure 9.2.** Comparison of UPC results with previous ones for M-.

To compare test results, it is necessary to transform the Karlsruhe ultimate loads in order to make them comparable.

\[ P_{\text{comp}} = \frac{5}{4} P_{\text{test}} \]

<table>
<thead>
<tr>
<th>UPC tests</th>
<th>Previous tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_u ) (kN)</td>
<td>( P_u ) (kN)</td>
</tr>
<tr>
<td><strong>Test n°1</strong></td>
<td>16,44</td>
</tr>
<tr>
<td><strong>Test n°2</strong></td>
<td>15,29</td>
</tr>
<tr>
<td><strong>Test n°3</strong></td>
<td>15,75</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>15,83</td>
</tr>
</tbody>
</table>

**Table 9.2.** Comparison of UPC results with previous ones for M-.

A summary of the ultimate loads and corresponding ultimate bending moments is presented in Table 9.3.
<table>
<thead>
<tr>
<th>Ultimate load (kN)</th>
<th>Experimental</th>
<th>Previous test</th>
<th>EN 1993-1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16,44</td>
<td>13,81</td>
<td>14,87</td>
</tr>
<tr>
<td></td>
<td>15,29</td>
<td>13,70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15,75</td>
<td>12,85</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate negative bending moment (kN)</th>
<th>Experimental</th>
<th>Previous test</th>
<th>EN 1993-1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6,17</td>
<td>5,18</td>
<td>5,58</td>
</tr>
<tr>
<td></td>
<td>5,73</td>
<td>5,14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5,91</td>
<td>4,82</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5,94</td>
<td>5,05</td>
<td>5,58</td>
</tr>
</tbody>
</table>

Table 9.3. Summary of results for negative bending moment.

10. CROSS SECTIONAL STIFFNESS ANALYSIS

Combining the load-displacement curves obtained in the positive and negative bending moment tests and the values of the material parameter obtained from tensile coupon tests analysis, the experimental cross sectional stiffness can be determined. First of all, the theoretical deflection of the sheet needs to be calculated.

In the determination of the deflection in the middle span section, expressions from simply supported beams subjected to same loading conditions have been used. The theoretical displacement in the middle span section is the following:

\[ w = 0,36 \cdot \frac{P}{E I} \]  

(eq. 10.1)

Where \( w \) is the deflection in the middle span section, \( P \) is the total applied load, \( E \) is the initial elastic modulus and \( I \) is the moment of inertia. Considering that \( P/w \) (named as \( K \)) is the stiffness that can be determined in the load-displacement curves, the experimental moment of inertia can be calculated and compared to the analytical one.

\[ I = 0,36 \cdot \frac{K}{E} \]  

(eq. 10.2)

Values of \( K \) can be determined calculating the regression lines in the experimental results. Table 10.1 summarizes the \( K \) (N/mm) values obtained for each test:

<table>
<thead>
<tr>
<th>Test</th>
<th>M+ test</th>
<th>M- test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>409,8</td>
<td>385,2</td>
</tr>
<tr>
<td>Test n°2</td>
<td>399,9</td>
<td>345,4</td>
</tr>
<tr>
<td>Test n°3</td>
<td>393,9</td>
<td>384,5</td>
</tr>
<tr>
<td>Mean value</td>
<td>401,2</td>
<td>371,7</td>
</tr>
</tbody>
</table>

Table 10.1. Experimental cross sectional stiffness.

Considering these results and the value of the initial elastic modulus determined in the tensile tests \( (E = 218104 \text{MPa}) \), the experimental moment of inertia can be obtained and compared to the analytical one as follows:
11. CONTINUOUS DECKING TEST RESULTS

Three continuous decking tests on two spans have been conducted in order to study bending-shear interaction in the middle support, so as to compare results with the ultimate bending moments obtained from previous single span tests.

The weight of the loading upper structure should be added to the load values obtained from load cell. The loading settings are 1800N in weight.

Four load-displacement curves were obtained in each test, with four linear variable differential transformer measuring linear displacement of the sheet along the vertical axis in the middle span section of each span.

In all the tests spreading of corrugations was prevent by using transverse ties under the loading sections. Load was applied by steel cross beams arranged to approximate uniformly distributed loading.

In the continuous tests a hinged support were placed in the internal support and roller supports at the end of the deck, that was connected to all the supports and bearing support sections were stiffened by using rectangular hollow sections and timber pieces.

During the tests, the middle support reaction was measured using two load cells. This gave some indications of when redistribution of moment occurred and allows determining the bending moment at any point in the sheet using equilibrium equations.

The results are presented as load-displacement curves (Figure 11.1) and a Table 11.1, summarizing the middle support collapse loads and the ultimate loads. The displacements were measured in the middle span section of the spans.

11.1 Load-displacement curves

All the load-displacement curves are presented in Annex A. Figure 11.1 shows the average curves between the measures of two displacement transducers situated in the same span for each continuous decking test. The same middle span transducers have been plotted for all the tests.
The load-displacement curves in Figure 11.1 show a change in the stiffness at the point when failure at the internal support occurred (36,95kN), but the structure does not collapse until a higher load is reached (40,74kN).

<table>
<thead>
<tr>
<th>Test</th>
<th>Middle support collapse load (kN)</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>37,17</td>
<td>40,45</td>
</tr>
<tr>
<td>Test 2</td>
<td>37,58</td>
<td>40,9</td>
</tr>
<tr>
<td>Test 3</td>
<td>36,10</td>
<td>40,86</td>
</tr>
<tr>
<td>Mean value</td>
<td>36,95</td>
<td>40,74</td>
</tr>
</tbody>
</table>

Table 11.1. Ultimate loads in the continuous decking tests.

11.2 **Middle support reaction evolution**

A linear elastic analysis of the structure can be done and it is possible to determine the relation between total load and support reactions in the elastic range.

![Diagram](image_url)

Figure 11.2. Double span test configuration.
Where \( R_A = R_C = 0,24395 \cdot Q_{ tot} \) and \( R_B = 0,5121 \cdot Q_{ tot} \)  \hspace{1cm} (eq. 11.1)

\( M_B = 0,1869 \cdot Q_{ tot} \) \hspace{1cm} (eq. 11.2)

\[ M_{ D-B} = (3-x) \cdot R_B - Q_{ tot} \cdot (4.05-x) /4 - Q_{ tot} \cdot (5.625-x) /4 + R_C \cdot (6-x) \] \hspace{1cm} (eq. 11.3)

The evolution of the experimental middle support reaction \( (R_B) \) from load cells is presented in Figure 11.3. This \( R_B \) reaction has been compared with the theoretical reaction value obtained from a linear analysis of the test, shown in eq.11.1. As it can be seen in Figure 11.3, there is some redistribution in the internal support because the reaction measured is different from the one calculated elastically after the middle support collapse.

![Middle support reaction](image)

Figure 11.3. Middle support reaction evolution for double span tests.

11.3 Bending moment evolution

Bending moment evolution at middle support (B) can be determined by using the total load and the load measured in the middle support with the load cells by eq. 11.3, with a value of \( x=3m \) for each test and experimental values of reactions. This experimental evolution can be also compared with the theoretical \( M_B \) value obtained from a linear analysis of the test, shown in eq.11.2. This comparison is shown in Figure 11.4.
The maximum bending moments (Mₘ) in the middle support can be calculated and presented in Table 11.2. The associate middle support reaction determined by the load cells is also presented.

<table>
<thead>
<tr>
<th>Test</th>
<th>Maximum bending moment in middle support (kN·m)</th>
<th>Middle support reaction (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test nº1</td>
<td>5,66</td>
<td>18,63</td>
</tr>
<tr>
<td>Test nº2</td>
<td>5,41</td>
<td>17,83</td>
</tr>
<tr>
<td>Test nº3</td>
<td>5,54</td>
<td>16,64</td>
</tr>
<tr>
<td>Mean</td>
<td>5,54</td>
<td>17,7</td>
</tr>
</tbody>
</table>

Table 11.2 Negative bending moments in the middle support

The bending moment evolution under the applied load near the middle support (M₀) can also be plotted (see Figure 11.5). The experimental values have been obtained from eq. 11.3 but with x=1,95 m but with the experimental values of Rₐ and Rₜ, and the linear one with the reaction values shown in eq. 11.1.
Positive bending moments under load application values \( (M_D) \) when the negative bending moment is maximum in the middle support and maximum positive bending moments under load application at the ultimate load are summarized in Table 11.3.

<table>
<thead>
<tr>
<th>Test</th>
<th>( M_D ) bending moment under load application when middle support collapses (kN·m)</th>
<th>( M_D ) maximum bending moment under load application at ultimate load (kN·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>3,72</td>
<td>7,86</td>
</tr>
<tr>
<td>Test n°2</td>
<td>3,95</td>
<td>7,63</td>
</tr>
<tr>
<td>Test n°3</td>
<td>3,52</td>
<td>7,37</td>
</tr>
<tr>
<td>Mean</td>
<td>3,73</td>
<td>7,62</td>
</tr>
</tbody>
</table>

Table 11.3 Positive \( M_D \) bending moments under load application section.

11.4 Continuous decking test figures

A selection of the most representative pictures of the continuous decking tests has been done herein, but more figures are gathered in Annex C.
Figure 11.6. General double span test configuration.

Figure 11.7. Sheet after overall collapse: hinge at middle support and under load application.

Figure 11.8. Sheet after overall collapse: hinge at middle support and under load application.
12. ANALYSIS OF RESULTS FOR CONTINUOUS DECKING TESTS

According to EN 1993-1-3 and EN 1993-1-4, bending moment-shear interaction at middle support determines the ultimate load of the system. This is usually a conservative approach because some negative bending moment redistribution occurs on middle support section and higher ultimate loads can be achieved, as it has been shown in Figure 11.1. In these tests the elastic bending resistance was reached at a 90% of the ultimate collapse load.

12.1 Comparison between continuous and simply supported tests

Comparing obtained ultimate failure bending moments for single and double span tests, the following conclusions can be drawn. Middle support section fails for a negative bending moment of 5,54kN·m for double span test, while the collapse negative bending moment is 5,94kN·m in single span tests. This reduction in the moment capacity for the internal support section in continuous beams is probably due to the interaction between bending moment and shear in this section.

12.2 Ultimate load predicted by EN 1993-1-3

Collapse of the middle support section: negative bending-reaction interaction

Shear-bending interaction can be determined using (eq. 12.1)

\[ \frac{R_{Id}}{R_{w,Rd}} + \frac{M_{Id}}{M_{c,Rd}} \leq 1.25 \]  

(eq. 12.1)
Where $M_{c,Rd}$ is the negative bending resistance calculated from (eq. 12.2). This resistance has already been calculated in negative bending moment test result analysis and has a mean value of $M_{c,Rd} = 5.57\text{kN} \cdot \text{m}$.

$$M_{c,Rd} = \frac{W_{e} f_{yb}}{\gamma M_{0}}$$

(eq. 12.2)

For the determination of the web crippling resistance, $R_{w,Rd}$, expressions in EN-1993-1-3 need to be considered. For sections with more than a single unstiffened web, the following expression (eq. 12.3) is defined:

$$R_{w,Rd} = n_{w} \alpha t^{2} \sqrt{\frac{\sigma_{0.2}}{E}} \left(1 - 0.1 \sqrt{\frac{r}{t}} \right) \left(0.5 + \sqrt{0.02 \frac{l_{a}}{t}} \left(2.4 + \left(\frac{\phi}{90}\right)^{2}\right) \right) \frac{1}{\gamma M_{1}}$$

(eq. 12.3)

This expression depends on geometrical parameters such as the internal radius ($r$), the thickness ($t$), the number of webs ($n_{w}$) and the relative angle between the web and the flange ($\phi$). Moreover, material mechanical properties are also considered including the Young modulus ($E$) and the material proof strength ($\sigma_{0.2}$), however, material nonlinearities are not taken into account. The values of both $l_{a}$ and $\alpha$ depend on the test configuration and the section type, which are ascribed accordingly the experiment category.

This test configuration corresponds to an internal support case, which is noted as Category 2 in EN 1993-1-3. Parameters corresponding to this cross section and test configuration are shown below and results in $R_{w,Rd} = 33.9\text{kN}$.

<table>
<thead>
<tr>
<th>$n_{w}$</th>
<th>10</th>
<th>$t$</th>
<th>0.8mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.15</td>
<td>$r$</td>
<td>3mm</td>
</tr>
<tr>
<td>$l_{a}$</td>
<td>60mm</td>
<td>$\Phi$</td>
<td>72°</td>
</tr>
</tbody>
</table>

Using $M_{Ed}$ and $R_{Ed}$ values presented in 11.2 (eq. 11.1 and eq. 11.2) and resistances shown above, an ultimate load of 25.69kN is predicted, with the corresponding middle support reaction, 13.16kN.

Some authors propose a new interaction expression for stainless steels [5] (eq. 12.4). For this new expression, the predicted ultimate loads are the following.

$$\frac{R_{Ed}}{R_{w,Rd}} + \frac{M_{Ed}}{M_{c,Rd}} \leq 1.4$$

(eq. 12.4)

In this case, a support reaction of 14.73kN and an ultimate load of 28.77kN are predicted.
These collapse experimental loads and the ones proposed by EN 1993-1-3 are summarized in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Middle support failure load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>36.95</td>
</tr>
<tr>
<td>EN 1993-1-3 (eq. 12.1)</td>
<td>25.69</td>
</tr>
<tr>
<td>New proposals (eq. 12.3)</td>
<td>28.77</td>
</tr>
</tbody>
</table>

Table 12.1. Experimental and analytical result comparison.

**13. INTERNAL SUPPORT TEST RESULTS**

Internal support test results for different span lengths are summarized herein. These tests were conducted in order to simulate an inverted deck element at the middle support.

For internal support tests the distance between the points with zero moment (noted as $L_u$) in the bending moment distribution is needed in order to determine the test span length. $L_e$ can be determined applying an elastic analysis of the structure below but also using data obtained from double span tests.

![Figure 13.1. Model schemes of the middle support behaviour [6].](image)
An elastic analysis of the structure presented in Figure 11.2 provides a value of \( L = 1,46 \text{m} \) between points with zero moment but calculating this distance with the experimental reactions measured during continuous decking tests instead of using the elastic ones, the following mean Le values are obtained for each test are:

<table>
<thead>
<tr>
<th>Test</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1,18</td>
</tr>
<tr>
<td>Test 2</td>
<td>1,15</td>
</tr>
<tr>
<td>Test 3</td>
<td>1,15</td>
</tr>
<tr>
<td>Mean</td>
<td>1,16</td>
</tr>
</tbody>
</table>

Table 13.1. Internal support length determination.

This later results are similar to the ones usually proposed in EN 1993-1-3, Annex A and the literature, where a span length of \( s = 0,4 \cdot L = 0,4 \cdot 3 \text{m} = 1,2 \text{m} \) is suggested. Then an internal support test with a span of 1200 mm has been considered. In order to characterize the bending moment-concentrate load interaction, other two span lengths have been considered (\( s = 705 \text{mm} \) and \( s = 430 \text{mm} \)).

Results are presented as load-displacement curves (figures 13.2 to 13.4) and ultimate loads and displacements summarized for each one of the tests are in Table 13.2. The displacements were measured in the middle span section of the sheet, in the loading section.

13.1 Load-displacement curves

Six load-displacement curves have been obtained for each internal support test. Only the average values measured under the load application section are plotted for each test in this section, but all the curves are presented in Annex A.

![Figure 13.2. Load-displacement curves for internal support test, \( s = 430 \text{mm} \).](image)
Figure 13.3. Load-displacement curves for internal support test, s=705mm.

Figure 13.4. Load-displacement curves for internal support test, s=1200mm.

<table>
<thead>
<tr>
<th>Span length</th>
<th>Test</th>
<th>Ultimate load (kN)</th>
<th>Displacement for the ultimate load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s=430mm</td>
<td>Test n°1</td>
<td>29,33</td>
<td>3,52</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>29,43</td>
<td>2,65</td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>29,43</td>
<td>3,22</td>
</tr>
<tr>
<td>s=705mm</td>
<td>Test n°1</td>
<td>25,33</td>
<td>3,98</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>25,73</td>
<td>4,31</td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>25,73</td>
<td>4,49</td>
</tr>
<tr>
<td>s=1200mm</td>
<td>Test n°1</td>
<td>18,03</td>
<td>8,52</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>17,43</td>
<td>8,70</td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>18,43</td>
<td>8,96</td>
</tr>
</tbody>
</table>
Table 13.2. Ultimate loads and displacements for internal support tests.

13.2 Internal support test figures

More internal support test figures are available in Annex C.

![Figure 13.5. General view of the internal support test configuration before and after collapse.](image)

![Figure 13.6. General and detailed view of the failed section.](image)

14. ANALYSIS OF RESULTS FOR INTERNAL SUPPORT TESTS

14.1 Ultimate load predicted by EN 1993-1-3

According to EN 1993-1-3, article 6.1.11, interaction between bending-moment and concentrate force needs to be checked in addition to the fundamental bending and load verifications (Eq. 14.1).

\[
\frac{F_{Ed}}{R_{w,Rd}} + \frac{M_{Ed}}{M_{c,Rd}} \leq 1.25
\]

(eq. 14.1)

\[
\frac{F_{Ed}}{R_{w,Rd}} \leq 1 \quad \frac{M_{Ed}}{M_{c,Rd}} \leq 1
\]

\(R_{w,Rd}\) is the web crippling resistance for an internal test configuration, defined as (eq. 14.2) in EN 1993-1-3, article 6.1.7.3 and \(M_{c,Rd}\) is the bending resistance (eq. 14.3). Considering the \(\alpha\) and \(I_a\) parameters for internal support tests in sheeting proposed in
Eurocode 3 and the parameters shown below, Table 14.1 summarizes resistance values for the studied section.

\[
R_{w,Rd} = n_w d^2 \sqrt{\sigma_{0.2} E \cdot (1 - 0.1 \sqrt{r / t}) \left(0.5 + \sqrt{0.02 l_a / t} \right)(2.4 + (\phi / 90)^2)} / \gamma_{M1} 
\]  
(eq. 14.2)

\[
M_{c,Rd} = \frac{W_{eff} \cdot f_{sh}}{\gamma_{M0}} 
\]  
(eq. 14.3)

For the negative bending position test, the effective section modulus is:

\[
W_{eff} (M-) = 17,43 \text{ cm}^3 
\]  
(eq. 14.4)

So the following resistance values have been considered:

\[
R_{w,Rd} = 33,9kN \\
M_{c,Rd} = 5,57kNm 
\]

<table>
<thead>
<tr>
<th>Span length</th>
<th>Test</th>
<th>Experimental ultimate load (kN)</th>
<th>EN 1993-1-3 predicted ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s=430mm</td>
<td>Test n°1</td>
<td>29,33</td>
<td>25,61</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>29,43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>29,43</td>
<td></td>
</tr>
<tr>
<td>s=705mm</td>
<td>Test n°1</td>
<td>25,33</td>
<td>20,44</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>25,73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>25,73</td>
<td></td>
</tr>
<tr>
<td>s=1200mm</td>
<td>Test n°1</td>
<td>18,03</td>
<td>14,99</td>
</tr>
<tr>
<td></td>
<td>Test n°2</td>
<td>17,43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test n°3</td>
<td>18,43</td>
<td></td>
</tr>
</tbody>
</table>

Table 14.1 Comparison between experimental and EN predicted loads for internal support tests.

As it has been explained before, some authors propose a new interaction expression for stainless steels [5] (eq. 14.5). For this new expression, the predicted ultimate loads are the following.

\[
\frac{F_{Ed}}{R_{w,Rd}} + \frac{M_{Ed}}{M_{c,Rd}} \leq 1.4 
\]  
(eq. 14.5)
### Table 14.2 Comparison between experimental and new expression predicted loads for internal support tests.

<table>
<thead>
<tr>
<th></th>
<th>ultimate load (kN)</th>
<th>predicted ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s=430mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°1</td>
<td>29,33</td>
<td>28,68</td>
</tr>
<tr>
<td>Test n°2</td>
<td>29,43</td>
<td></td>
</tr>
<tr>
<td>Test n°3</td>
<td>29,43</td>
<td></td>
</tr>
<tr>
<td>s=705mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°1</td>
<td>25,33</td>
<td>22,89</td>
</tr>
<tr>
<td>Test n°2</td>
<td>25,73</td>
<td></td>
</tr>
<tr>
<td>Test n°3</td>
<td>25,73</td>
<td></td>
</tr>
<tr>
<td>s=1200mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°1</td>
<td>18,03</td>
<td>16,79</td>
</tr>
<tr>
<td>Test n°2</td>
<td>17,43</td>
<td></td>
</tr>
<tr>
<td>Test n°3</td>
<td>18,43</td>
<td></td>
</tr>
</tbody>
</table>

Considering the experimental ultimate negative bending resistance (obtained in sections 8 and 9), the experimental interaction diagram can be obtained considering the studied different span lengths. As pure concentrate load resistance could not be obtained from the conducted tests (in absence of bending moment), EN predicted load has been used herein for Ru, so Figure 14.1 shows approximate values.

#### Figure 14.1. Bending-concentrate force interaction for internal support tests.

14.2 **Moment-rotation diagrams**

According to EN 1993-1-31-3, Annex A, moment-rotation diagrams should be plotted for each tests (*article A.5.2.3*). The rotation $\theta$ can be obtained for values of the applied load when working with on the gross cross section by (eq. 14.6):
\[ \theta = \frac{2(\delta_{pl} - \delta_s - \delta_{lin})}{0.5s - e} \]  (eq. 14.6)

Where
- \( \delta_{pl} \) is the net deflection for the same load on the falling part of the curve after \( F_{max} \).
- \( \delta_s \) is the average deflection measured at a distance \( e \) from the support.
- \( \delta_{lin} \) is the fictive net deflection for a given load obtained with a linear behaviour.
- \( e \) is the distance between a deflection measurement point and a support.
- \( s \) is the test span.

Relationship between \( M \) and \( \theta \) should be plotted for each test at a given test span \( s \). The design \( M-\theta \) characteristic for the moment resistance of the beam over an internal support should then be taken as equal to 0.9 times the mean value of \( M \) for all the tests corresponding to that value of the test span \( s \).

Figures 14.3 to 14.5 show the corresponding moment-rotation curves for each test span length, showing \( M-\theta \) curves for each test, the mean curve between them and the design \( M-\theta \) curve. Figure 14.6 also compares the mean values of the \( M-\theta \) curves for each considered span length.
Figure 14.3. Moment-rotation curves for internal support test, s=430mm.

Figure 14.4. Moment-rotation curves for internal support test, s=705mm.
14.3 Comparison with similar test results

Previously presented results can be compared to the ones published by the Universität Karlsruhe [4], because some of the tested span lengths are the same or very similar.

As explained in negative bending test result analysis, it is important to note that the cross section tested in Universität Karlsruhe was shorter than the one used in this study, involving just 4 waves instead of the original 5, so it is necessary to transform the Karlsruhe ultimate loads in order to make them comparable.
Table 14.3. Comparison of UPC results with previous ones for internal support tests for s=430mm.

<table>
<thead>
<tr>
<th>UPC tests</th>
<th>Previous tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P_u (kN)</strong></td>
<td><strong>P_u (kN)</strong></td>
</tr>
<tr>
<td><strong>Test n°1</strong></td>
<td>29,33</td>
</tr>
<tr>
<td><strong>Test n°2</strong></td>
<td>29,43</td>
</tr>
<tr>
<td><strong>Test n°3</strong></td>
<td>29,43</td>
</tr>
</tbody>
</table>

Table 14.4. Comparison of UPC results with previous ones for internal support tests for s=705mm.

<table>
<thead>
<tr>
<th>UPC tests</th>
<th>Previous tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P_u (kN)</strong></td>
<td><strong>P_u (kN)</strong></td>
</tr>
<tr>
<td><strong>Test n°1</strong></td>
<td>25,33</td>
</tr>
<tr>
<td><strong>Test n°2</strong></td>
<td>25,73</td>
</tr>
<tr>
<td><strong>Test n°3</strong></td>
<td>25,73</td>
</tr>
</tbody>
</table>

15. END SUPPORT TEST RESULTS

Conducted end support test results are summarized herein. These results are presented as load-displacement curves (figures 15.1 and 15.2) and Table 15.1, summarizing the ultimate loads and displacements (on middle span section) for each one of the tests.

15.1 Load-displacement curves

Tests 1 and 3 were conducted with u=40mm, while tests 2 and 4 were u=60mm. This difference can be seen on both figures, for displacements measured in the middle span section and in the support section.

Tests with u=60mm were conducted on previous tested sheets for u=40mm, because the edge opposite to the tested one remained almost undistorted, so it was decided to use these sheets in order to conduct more tests and get some extra information. Nevertheless, some influence of the previous loading of the sheets was seen in later analysis, discussed in 16.3.

As the section which is supposed to fail is the not-protected support section (end support), the ultimate load needs to be converted to support reaction. As EN 1993-1-3, Annex A proportions were considered, the reaction is 2/3 of the ultimate applied load.
Load-displacement curve in the support section for Test 1 does not reach the experimental ultimate load because displacement transducers measuring support displacements were saturate before the test was over. The position of these transducers was therefore corrected for the following end support tests.

### Table 15.1. Achieved ultimate loads and displacements for end support tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Ultimate load $F_u$ (kN)</th>
<th>Ultimate reaction $R_u = 2/3 \cdot F_u$ (kN)</th>
<th>Displacement for the ultimate load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>45,75</td>
<td>30,19</td>
<td>11,31</td>
</tr>
<tr>
<td>Test n°2</td>
<td>45,94</td>
<td>30,32</td>
<td>8,20</td>
</tr>
<tr>
<td>Test n°3</td>
<td>44,39</td>
<td>29,30</td>
<td>11,70</td>
</tr>
<tr>
<td>Test n°4</td>
<td>45,59</td>
<td>30,10</td>
<td>7,89</td>
</tr>
</tbody>
</table>
15.2 End support test figures

![Figure 15.3. General view of the end support test configuration before and after collapse.](image)

![Figure 15.4. General and detailed view of the failed section.](image)

16. ANALYSIS OF RESULTS FOR END SUPPORT TESTS

16.1 Ultimate load predicted by EN 1993-1-3

According to EN 1993-1-3, the resistance verification for end support tests is the following:

\[
\frac{F_{Ed}}{R_{w,Rd}} \leq 1 \quad \text{(eq. 16.1)}
\]

Where \( R_{w,Rd} \) is the web crippling resistance, defined as (eq. 16.2) in EN 1993-1-3, article 6.1.7.3. Considering the \( \alpha \) and \( l_a \) parameters for end support tests in sheeting proposed in Eurocode 3, Table 16.1 summarizes resistance values for the studied section. The most important parameters are shown herein:

| \( n_w \) | 10 | t | 0.8mm |
| \( \alpha \) | 0.075 | r | 3mm |
| \( l_a \) | 10mm | \( \Phi \) | 72° |
\[ R_{w,Rd} = n_w d^2 \sqrt{\sigma_{0.2}E} \left(1 - 0.1 \sqrt{r/t} \right) \left(0.5 + \sqrt{0.02 l_a/t} \right) (2.4 + (\phi/90)^2) / \gamma_M \]

(eq. 16.2)

In internal support tests, \( l_a \) is considered as the bearing length of the load application section in EN 1993-1-3 formulation, while in end support tests this parameter remains constant and equal to 10mm. The same expression but with a different \( l_a \) value (equal to the bearing length, 30mm in this case) can be also used to predict the end support resistance. This result is shown in Table 16.1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Experimental ultimate reaction (kN)</th>
<th>EN 1993-1-3 predicted ultimate reaction (kN) ((l_a=10\text{mm}))</th>
<th>EN 1993-1-3 predicted ultimate reaction (kN) ((l_a=S_e =30\text{mm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>30,19</td>
<td>9,83</td>
<td>13,43</td>
</tr>
<tr>
<td>Test n°2</td>
<td>30,32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°3</td>
<td>29,30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°4</td>
<td>30,10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16.1 Comparison between experimental and EN predicted loads for end support tests.

Comparing experimental and analytical ultimate loads, it can be noticed that EN 1993-1-3 values are too conservative. It is important to notice, though, that the failure mechanism on the conducted end support tests was not the typical support section failure. Sheets finally collapsed due to a bending moment-shear interaction, similar to the internal support tests and not at the support.

Analyzing end support tests as internal support ones, the EN 1993-1-3 predicted loads are the following:

<table>
<thead>
<tr>
<th>Test</th>
<th>Experimental ultimate reaction (kN)</th>
<th>EN 1993-1-3 predicted ultimate reaction (kN) ((eq.14.1 \text{ interaction}))</th>
<th>EN 1993-1-3 predicted ultimate reaction (kN) ((eq.14.2 \text{ interaction}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test n°1</td>
<td>30,19</td>
<td>20,59</td>
<td>23,06</td>
</tr>
<tr>
<td>Test n°2</td>
<td>30,32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°3</td>
<td>29,30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test n°4</td>
<td>30,10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16.2 Comparison between experimental and EN predicted loads for end support tests but considering them as internal support tests.

Those new predicted values are closer than the ones provided in Table 16.1, but are still considerably conservative. This could be because the support section weakens the whole structure, reaching a lower ultimate load. Anyway, these tests ensure that the sheet collapse will not happened on the edge support, but in the middle span section.

It is also important to highlight that end support test configuration proposed in EN 1993-1-3, Annex A was originally designed for plain sheeting without embossments and its applicability to the sheets used in this study is being revised.

Probably the resistance to shear local buckling in the webs is highly increased by the embossments.
16.2 Comparison with similar test results

Previously presented results can be compared to the ones published by the Universität Karlsruhe [4], proportions between introduced loads and support reactions are the same.

<table>
<thead>
<tr>
<th>UPC tests</th>
<th>Previous tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P_u (kN)</td>
</tr>
<tr>
<td>Test n°1</td>
<td>45,75</td>
</tr>
<tr>
<td>Test n°2</td>
<td>45,94</td>
</tr>
<tr>
<td>Test n°3</td>
<td>44,39</td>
</tr>
<tr>
<td>Test n°4</td>
<td>45,59</td>
</tr>
</tbody>
</table>

Table 16.2. Comparison of UPC results with previous ones for end support tests.

16.3 Comparison between u=40mm and u=60mm tests

As it is shown on Figures 15.1 and 15.2, some difference in sheet behavior can be observed between u=40mm and u=60mm tests. Although reached ultimate loads are almost equal, displacement at the collapse moment is lower for tests with u=60mm. This is because sheets where this tests were conducted were previously tested with the u=40mm ones, so they were subjected to some initial deformations and residual stresses. Consequently, it can be seen that previous sheeting deformation causes a reduction in the deformation capacity, but not on the ultimate load capacity.
17. CONCLUSIONS

The study carried out on the embossments has shown some scattering in the height with significantly lower values than the nominal one and was not noticed during the first controls of the profiling trials. This remark is not specific to stainless steel since similar drifting toward lower embossment height was also noticed recently on galvanized steel, although at a lower level. Although the embossment geometry don't significantly affect to the decking test behaviour, they will affect the load transfer in the steel-concrete interface behaviour of the composite slab.

Experimental results on simply supported cold-formed trapezoidal sheets show that the ultimate load predicted by the existing standards provides a safe result, for the positive and the negative bending position, confirming the applicability of EN 1993-1-3 design rules for carbon steel to ferritic stainless steels.

The accuracy of the EN 1993-1-3 proposals to determine the local and distortional buckling stresses have also been checked. Critical stresses calculated from these expressions are very similar to the ones obtained experimentally during positive and negative bending tests, so the applicability of those equations can also be confirmed.

The comparison of the experimental results on simply supported tests with the ones from the previous tests conducted on carbon steel cold-formed trapezoidal sheets, assures that they were well conducted and that the obtained data is truthful. On the other hand, it is important to remark that the difference between the negative bending position results is due to the different test configuration.

Continuous decking tests on 2x3m spans have been also conducted. Obtained load-displacement curves have shown a change in the system stiffness when the internal support failed and this failure occurred at 90% of the ultimate load.

According to EN 1993-1-3, the decks need to be studied elastically and the load resistance of the system is determined by the bending moment-reaction interaction for the internal support. As some moment redistribution due to elastic variation of stiffness and local post-elastic deformation has been identified by measuring the reaction at the internal support by load cells, this is a conservative approach.

Therefore, it can be concluded that EN 1993-1-3 proposals are applicable to ferritic stainless steel although further research should be done in order to evaluate the ultimate loading capacity of the decks due to moment redistribution and include this analysis in Standards.

Internal support tests, with different span lengths, were also conducted to determine the correct negative bending moment-reaction interaction for ferritic stainless steel decking. EN 1993-1-3 interaction proposals provide safe results for the studied decks, although they are quite conservative. Otherwise, the interaction proposal suggested by other authors for stainless steels provides more accurate results.

Similar ultimate loads were obtained in ferritic stainless steel and carbon steel decking internal support tests for different test span lengths, even if results for the ferritic decks were quite higher.
Moment-rotation curves were also determined for different internal support span lengths to determine whether a plastic design can be applied to continuous decking tests. As moment-rotation diagrams need to have a long plateau part to guarantee a post-elastic behaviour and permit a plastic analysis.

Finally, end support tests were conducted in order to evaluate the web crushing resistance of the decks in outer supports. It can be concluded that EN 1993-1-3 proposals for web crushing are too conservative. Nevertheless, it was noticed that the failure mechanism was a bending moment-concentrate load interaction for all the end support tests, so the studied decks are expected to fail in the middle span section before the web crushing resistance is reached in outer supports.

These tests also highlighted the need of new suggestions for the definition of end support tests in EN 1993-1-3, Annex A for decks similar to the ones studied here where the ultimate web crushing resistance can be evaluated. Ultimate loads reached in carbon steel decking tests are very similar to the ones presented in this work, what guarantees that the tests were correctly performed.

18. REFERENCES

Annex A: Tests Results

POSITIVE BENDING MOMENT TESTS

SAFSS_UPC  1 span M+ L = 3000 mm  n°1
SAFSS_UPC 1 span M+ L=3000 mm nº2 (Gauges)

Force cylinder + Load system vs d (mm) Displacements

F (N)
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000

0 10 20 30 40 50 60 70 80 90 100 110 120 d (mm)
SAFSS_UPC  1 span  M+ L =3000 mm  nº3
NEGATIVE BENDING MOMENT TESTS

SAFSS_UPC  1 span  M-  L =3000 mm  n°1

F (N)  Force cylinder + Load system

d (mm)  Displacements

0  10  20  30  40  50  60  70  80  90  100  110  120
0  1000  2000  3000  4000  5000  6000  7000  8000  9000  10000  11000  12000  13000  14000  15000  16000  17000

Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage
Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage

SAFSS_UPC  1 span M- L =3000 mm n°2
SAFSS_UPC  1 span M- L =3000 mm nº3 Gauges

F (N)  

0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000 17000

0 10 20 30 40 50 60 70 80 90 100 110 120

d (mm)  Displacements

Force cylinder + Load system.
CONTINUOUS DECKING TESTS

SAFSS_UPC  Two spans  3000+3000 mm  nº1

F (N)  Force cylinder + Load system

d (mm)  Displacements
SAFSS_UPC  Two spans  3000+3000 mm nº2
SAFSS_UPC  Two spans  3000+3000 mm  n°3

Force cylinder + Load system

F (N)

0  2000  4000  6000  8000  10000  12000  14000  16000  18000  20000  22000  24000  26000  28000  30000  32000  34000  36000  38000  40000  42000

d (mm)  Displacements

0  10  20  30  40  50  60  70  80  90  100
INTERNAL SUPPORT TESTS

SAFSS_UPC   IST 430mm nº1

F (N)  Force cylinder + Load system

d (mm)  Displacements
SAFSS_UPC   IST 430mm nº3

Force cylinder + Load system

F (N)

Displacements

d (mm)
SAFSS_UPC  IST 705mm nº1

\[ F(N) \]

\[ d\text{ (mm)} \quad \text{Displacements} \]
SAFSS_UPC  IST 705mm n°2

Force cylinder + Load system

F (N)  d (mm)  Displacements

0  0  1000  2000  3000  4000  5000  6000  7000  8000  9000
1 0000  2 0000  3 0000  4 0000  5 0000  6 0000  7 0000  8 0000  9 0000
SAFSS_UPC   IST 705mm n°3

$F \text{ (N)}$

$\text{d (mm)}$  Displacements

Force cylinder + Load system
SAFSS_UPC  IST 1200mm nº2

![Graph showing force (F) vs. displacement (d) for various load systems.](chart.png)
SAFSS_UPC IST 1200mm nº3

F (N) vs. d (mm) disjointed graph showing Force cylinder + Load system. The graph plots force in Newtons (F) on the y-axis against displacement in millimeters (d) on the x-axis. The curves represent different scenarios or conditions, each indicated by a distinct color. The graph is labeled with axis labels and units: Force cylinder + Load system for the y-axis, d (mm) for the x-axis, and Displacements.
END SUPPORT TESTS
SAFSS  EST  600mm  nº2

F (N) - Force cylinder + Load system

d (mm) - Displacements
SAFSS  EST  600mm  nº3

- Force cylinder + Load system

Displacements

F (N) vs. d (mm)
SAFSS  EST  600mm  nº4

- **F (N)**: Force cylinder + Load system

- **d (mm)**: Displacements

- **SAFSS**
- **EST**
- **600mm**
- **nº4**
Annex B: Gauge Results

POSITIVE BENDING MOMENT TESTS:

The stress-strain curves of each of the strain gauges placed on the second test, for the positive bending position of the profile, are shown as follows:

The gauge distribution along the cross section is shown in Figures B.1, B.2 and B.3.

![Wave 1, Wave 3, Wave 5](image)

Figure B.1. Wave labelling along the cross section.

![Gauge labelling and distribution in waves 1 and 5](image)

Figure B.2. Gauge labelling and distribution in waves 1 and 5, respectively.

![Gauge labelling and distribution in wave 3](image)

Figure B.3. Gauge labelling and distribution in wave 3.

Deformation measures in both top and bottom fibres allow determining the membrane deformation in the sheet, defining the strain distribution in the cross section and obtaining the deformed planes.
Figure B.10 Load-deformation plot for gauge nº7
Figure B.11 Load-deformation plot for gauge nº8
Figure B.12 Load-deformation plot for gauge nº9
Figure B.13 Load-deformation plot for gauge nº10
Figure B.14 Load-deformation plot for gauge nº11
Figure B.15 Load-deformation plot for gauge nº12
Figure B.16 Load-deformation plot for gauge n°13

Figure B.17 Load-deformation plot for gauge n°14

Figure B.18 Load-deformation plot for gauge n°15

Figure B.19 Load-deformation plot for gauge n°16

Figure B.20 Load-deformation plot for gauge n°17

Figure B.21 Load-deformation plot for gauge n°18
Figure B.22 Load-deformation plot for gauge nº19

Figure B.23 Load-deformation plot for gauge nº20

Figure B.24 Load-deformation plot for gauge nº21

Figure B.25 Load-deformation plot for gauge nº22

Figure B.26 Load-deformation plot for gauge nº23

Figure B.27 Load-deformation plot for gauge nº24
Figure B.28 Load-deformation plot for gauge n°25

Figure B.29 Load-deformation plot for gauge n°26

Membrane deformation in compression

Membrane deformation in tension
NEGATIVE BENDING MOMENT TESTS:
The stress-strain curves of each of the strain gauges placed on the third test, for the negative bending position of the profile, are shown as follows:

The gauge distribution along the cross section is shown in Figures B.30, B.31 and B.32.

Figure B.30. Wave labelling in cross section.
Deformation measures in both top and bottom fibres allow determining the membrane deformation in the sheet, defining the strain distribution of the cross section and obtaining the deformed planes.

Figure B.31. Gauge labelling and distribution in waves 1 and 5 respectively.

Figure B.32. Gauge labelling and distribution in wave 3.

Figure B.33 Load-deformation plot for gauge n°1

Figure B.34 Load-deformation plot for gauge n°2
Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage

Figure B.35 Load-deformation plot for gauge nº3
Figure B.36 Load-deformation plot for gauge nº4
Figure B.37 Load-deformation plot for gauge nº5
Figure B.38 Load-deformation plot for gauge nº6
Figure B.39 Load-deformation plot for gauge nº7
Figure B.39 Load-deformation plot for gauge nº8
Figure B.40 Load-deformation plot for gauge nº9

Figure B.41 Load-deformation plot for gauge nº10

Figure B.42 Load-deformation plot for gauge nº11

Figure B.43 Load-deformation plot for gauge nº12

Figure B.44 Load-deformation plot for gauge nº13

Figure B.45 Load-deformation plot for gauge nº14
**Figure B.46 Load-deformation plot for gauge nº15**

**Figure B.47 Load-deformation plot for gauge nº16**

**Figure B.48 Load-deformation plot for gauge nº17**

**Figure B.49 Load-deformation plot for gauge nº18**

**Membrane deformation in tension**

- **G3-10**
- **G5-12**
- **G4-11**
Annex C Pictures

POSITIVE BENDING MOMENT TEST
Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage
Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage
NEGATIVE BENDING MOMENT TEST
CONTINUOUS DECKING TESTS
Structural Applications of Ferritic Stainless Steels
WP3.2: Decking tests in the construction stage
INTERNAL SUPPORT TESTS
Structural Applications of Ferritic Stainless Steels

WP3.2: Decking tests in the construction stage
END SUPPORT TESTS
<table>
<thead>
<tr>
<th>WP3.2: Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decking tests in the construction stage</td>
</tr>
</tbody>
</table>