REPORT

No.: D3.3 – part 5

Introduction of loads into axially loaded sandwich panels

Publisher: Saskia Käpplein
            Thomas Misiek
            Karlsruher Institut für Technologie (KIT)
            Versuchsanstalt für Stahl, Holz und Steine

Task: 3.4
Object: Design of axially loaded sandwich panels - load application areas

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<tr>
<td>Industrial Project Leader</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_F$</td>
<td>cross section area of face</td>
</tr>
<tr>
<td>$E_F$</td>
<td>elastic modulus of face</td>
</tr>
<tr>
<td>$E_C$</td>
<td>elastic modulus of core</td>
</tr>
<tr>
<td>$G_C$</td>
<td>shear modulus of core</td>
</tr>
<tr>
<td>$I_F$</td>
<td>moment of inertia of a face</td>
</tr>
<tr>
<td>$E_{IF}$</td>
<td>bending stiffness of a face</td>
</tr>
<tr>
<td>$N_{cr}$</td>
<td>elastic buckling load</td>
</tr>
<tr>
<td>$c$</td>
<td>stiffness of elastic foundation</td>
</tr>
<tr>
<td>$t_F$</td>
<td>thickness of face</td>
</tr>
<tr>
<td>$f_{y,F}$</td>
<td>yield strength of face</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>imperfection factor (equivalent member method)</td>
</tr>
<tr>
<td>$\lambda_w$</td>
<td>slenderness of face (wrinkling in mid-span)</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>slenderness of face (crippling of free edge)</td>
</tr>
<tr>
<td>$\nu_C$</td>
<td>Poisson ratio of core material</td>
</tr>
<tr>
<td>$\nu_F$</td>
<td>Poisson ratio of face sheet</td>
</tr>
<tr>
<td>$\sigma_{cr,w}$</td>
<td>elastic buckling stress (wrinkling in mid-span)</td>
</tr>
<tr>
<td>$\sigma_{cr,c}$</td>
<td>elastic buckling stress (crippling of free edge)</td>
</tr>
<tr>
<td>$\sigma_w$</td>
<td>wrinkling stress</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>crippling stress</td>
</tr>
<tr>
<td>$\chi_w$</td>
<td>reduction factor for wrinkling (equivalent member method)</td>
</tr>
<tr>
<td>$\chi_c$</td>
<td>reduction factor for crippling (equivalent member method)</td>
</tr>
</tbody>
</table>
1 Introduction

Until now the common application of sandwich panels is restricted to the function of space enclosure. The sandwich panels are mounted on a substructure and they transfer transverse loads as wind and snow to the substructure. The sandwich panels are subjected to bending moments and transverse forces only. A new application is to apply sandwich panels with flat or lightly profiled faces in smaller buildings – such as cooling chambers, climatic chambers and clean rooms – without any load transferring substructure (Fig. 1.1).

![Building made of sandwich panels but without substructure](image)

**Fig. 1.1:** Building made of sandwich panels but without substructure

In this new type of application in addition to space enclosure, the sandwich panels have to transfer loads and to stabilise the building. In addition to the moments and transverse forces resulting from transverse loads, the wall panels transfer normal forces arising from the superimposed load from overlying roof or ceiling panels. Within the framework of work package 3 of the EASIE project, design methods for axially loaded sandwich panels have been developed. In Deliverable D3.3 – part 4 [1] design procedures for global design are introduced. The report at hand deals with the design of the areas of load application, i.e. with the lower end of the panel and at the connection between wall and roof, where the superimposed loads from the roof are applied as normal force into the wall panel. Load application details, at which the normal force is introduced by contact, are considered in the report. Tests on load application details were performed. The tests are documented in test report D3.2 – part 5 [2]. Based on these tests and on numerical calculations a procedure for the design of the load application area is derived. With this procedure the load bearing capacity of the load application area can be determined based on the wrinkling stress of the compressed face.
2 Load application details

The report at hand deals with load application areas, e.g. the connection between wall and roof. Two examples of load application details are shown in Fig. 2.1. At the load application area the axial force is introduced from the roof into the wall or from the wall into the foundation by contact.

Fig. 2.1: Examples of load application details

Amongst other things ETAG 21 [8] deals also with the design of axially loaded panels. A test procedure for determination of the resistance to axial loads is given in Annex D of ETAG 21. In these tests the assembly of a wall panel and its fixings is tested. The panel is fixed to the foundation as in practice. Also the load is introduced as in the intended application.

Fig. 2.2: Test according to ETAG 21 for centric and eccentric axial load

So by tests according to ETAG 21 the resistance to axial loads is determined for the tested configuration of panel and fixing only. There are only few possibilities to use a resistance
value, which is determined by these tests, for any other configuration. Furthermore ETAG 21 makes no distinction between the global load-bearing capacity of the panel and the local load bearing capacity of the load application area. No general resistance values, which can be used for a generalized design method, are determined, by the procedures according to ETAG 21.

3 Tests on load application details

3.1 Tested specimens

Different tests on load application details, where the loads are introduced as a normal force into the face of a panel, were performed. For all tests specimens with the width 400 mm have been used. The tested specimens had the length of approximately 300 mm – 400 mm. Panels with steel faces and different core materials have been tested. A summary of the tested types of panels is given in the following table.

<table>
<thead>
<tr>
<th>No.</th>
<th>core material</th>
<th>thickness of panel [mm]</th>
<th>face material</th>
<th>thickness of faces [mm]</th>
<th>profiling of faces</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PU</td>
<td>100</td>
<td>steel</td>
<td>0,50</td>
<td>lightly profiled</td>
</tr>
<tr>
<td>B *)</td>
<td>PU</td>
<td>100</td>
<td>steel</td>
<td>0,75</td>
<td>lightly profiled</td>
</tr>
<tr>
<td>C</td>
<td>EPS</td>
<td>100</td>
<td>steel</td>
<td>0,60</td>
<td>flat</td>
</tr>
<tr>
<td>E</td>
<td>MW</td>
<td>100</td>
<td>steel</td>
<td>0,50</td>
<td>lightly profiled</td>
</tr>
</tbody>
</table>

*) discontinuous produced panel

Tab. 3.1: Tested types of sandwich panels

For each tested type of panel the mechanical properties of the face sheets and of the core material were determined. In addition bending tests to determine the wrinkling stress of the faces have been performed.

From the face sheets specimens for tensile tests according to EN 10002-1 were worked out and tensile tests for determining the mechanical properties of surface layers were done. For the determination of the yield strength \( R_{yH}/R_{p0,2} \) and the tensile strength \( R_m \) the core thicknesses \( t_c \) determined on the specimens were used. The mean values of the results are listed in Tab. 3.2.
Tab. 3.2: Mechanical properties of the faces (mean values)

<table>
<thead>
<tr>
<th>type of panel</th>
<th>fK [mm]</th>
<th>Reh/Rp0,2 [N/mm²]</th>
<th>Rm [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, bottom side of production</td>
<td>0,472</td>
<td>358</td>
<td>403</td>
</tr>
<tr>
<td>B, top side of production</td>
<td>0,765</td>
<td>399</td>
<td>403</td>
</tr>
<tr>
<td>C, face 2</td>
<td>0,541</td>
<td>406</td>
<td>453</td>
</tr>
<tr>
<td>E, face 2</td>
<td>0,476</td>
<td>472</td>
<td>479</td>
</tr>
</tbody>
</table>

The mechanical properties of the core layer were determined according to EN 14509 [3]. The determination of the compression strength fCc, the tensile strength fCt, the shear strength fCv, as well as the appropriate shear, compression and tensile module values GC, ECc and ECt was realized on at least three specimens. The analysis of the modulus of elasticity EC was realised as mean value from the compression and tensile module of a specimen pair. The mean values of the results are listed in Tab. 3.3 and Tab. 3.4.

Tab. 3.3: Mechanical properties of the core layer – strength (mean values)

<table>
<thead>
<tr>
<th>No.</th>
<th>fCv [N/mm²]</th>
<th>fCc [N/mm²]</th>
<th>fCt [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0,09</td>
<td>0,10</td>
<td>0,14</td>
</tr>
<tr>
<td>B</td>
<td>0,11</td>
<td>0,19</td>
<td>0,21</td>
</tr>
<tr>
<td>C</td>
<td>0,10</td>
<td>0,15</td>
<td>0,16</td>
</tr>
<tr>
<td>E</td>
<td>0,08</td>
<td>0,09</td>
<td>0,12</td>
</tr>
</tbody>
</table>

Tab. 3.4: Mechanical properties of the core layer – module (mean values)

<table>
<thead>
<tr>
<th>No.</th>
<th>GC [N/mm²]</th>
<th>ECc [N/mm²]</th>
<th>ECl [N/mm²]</th>
<th>EC [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2,93</td>
<td>2,95</td>
<td>3,24</td>
<td>3,10</td>
</tr>
<tr>
<td>B</td>
<td>3,56</td>
<td>3,83</td>
<td>6,32</td>
<td>5,08</td>
</tr>
<tr>
<td>C</td>
<td>4,18</td>
<td>6,38</td>
<td>10,56</td>
<td>8,47</td>
</tr>
<tr>
<td>E</td>
<td>9,82</td>
<td>9,33</td>
<td>12,08</td>
<td>10,71</td>
</tr>
</tbody>
</table>

To determine the wrinkling stress single-span bending tests were performed with every type of sandwich panel. The sandwich panels with a length of 6000 mm were loaded until failure in a vacuum chamber under uniform surface load. For the calculation of the wrinkling stress the
measured core thickness of the steel faces and the measured thickness of the panels were used. The results of the single-span bending tests are listed in Tab. 3.5.

<table>
<thead>
<tr>
<th>type of panel</th>
<th>thickness of panel (mean value)</th>
<th>width of panel</th>
<th>span</th>
<th>core sheet thickness of compressed face</th>
<th>failure load incl. dead weight</th>
<th>wrinkling stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[mm] [mm] [mm] [mm] [kN/m] [N/mm²]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>A top side of production</td>
<td>99,4</td>
<td>1176</td>
<td>5700</td>
<td>0,474</td>
<td>2,69</td>
</tr>
<tr>
<td></td>
<td>bottom side of production</td>
<td>99,3</td>
<td>1178</td>
<td>5700</td>
<td>0,472</td>
<td>2,75</td>
</tr>
<tr>
<td>B</td>
<td>A top side of production</td>
<td>98,9</td>
<td>1194</td>
<td>5700</td>
<td>0,765</td>
<td>4,41</td>
</tr>
<tr>
<td></td>
<td>bottom side of production</td>
<td>89,9</td>
<td>1195</td>
<td>5700</td>
<td>0,759</td>
<td>4,43</td>
</tr>
<tr>
<td>C</td>
<td>face 1</td>
<td>100,3</td>
<td>1196</td>
<td>5700</td>
<td>0,538</td>
<td>2,79</td>
</tr>
<tr>
<td></td>
<td>face 2</td>
<td>100,2</td>
<td>1196</td>
<td>5700</td>
<td>0,541</td>
<td>2,76</td>
</tr>
<tr>
<td>E</td>
<td>face 1</td>
<td>99,4</td>
<td>999</td>
<td>5800</td>
<td>0,475</td>
<td>1,17</td>
</tr>
<tr>
<td></td>
<td>face 2</td>
<td>99,5</td>
<td>999</td>
<td>5800</td>
<td>0,475</td>
<td>1,51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>99,4</td>
<td>1000</td>
<td>5800</td>
<td>0,475</td>
<td>1,69</td>
</tr>
</tbody>
</table>

Tab. 3.5: Wrinkling stress of the faces

Furthermore the geometry of the lightly profiled faces was measured and the bending stiffness \( E_{IF} \) and the cross section area \( A_{IF} \) of the faces were determined. The measured geometries are given in Fig. 3.1. Tab. 3.6 shows the calculated bending stiffness's and areas.

<table>
<thead>
<tr>
<th>type of panel</th>
<th>area ( A_{IF} ) [mm²/mm]</th>
<th>moment of inertia ( I_{IF} ) [mm⁴/mm]</th>
<th>bending stiffness ( E_{IF} ) [Nmm²/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0,474</td>
<td>0,0764</td>
<td>17635</td>
</tr>
<tr>
<td>B</td>
<td>0,762</td>
<td>0,1267</td>
<td>29242</td>
</tr>
<tr>
<td>C</td>
<td>0,540</td>
<td>0,0144</td>
<td>3028</td>
</tr>
<tr>
<td>E</td>
<td>0,475</td>
<td>0,0194</td>
<td>4477</td>
</tr>
</tbody>
</table>

Tab. 3.6: Area and bending stiffness of faces
Panel type A:

Panel type B:

Panel type E:

Fig. 3.1:  Geometry of the faces

To fix the specimens to the test set-up aluminium angles were glued and additionally screwed to the faces at the lower end of the specimens. The angles were screwed to a wooden board, which could be easily fixed to the test set-up (Fig. 3.2).

Fig. 3.2:  Lower end of the tested specimens
3.2 Introduction of loads by contact

Tests to determine the load bearing capacity of the free cut edge of the panels were performed. The load was introduced by contact. The test set-up is shown in Fig. 3.3 und Fig. 3.4. For introducing the load into the face of the panel a plate of steel has been used. For comparison instead of a plate of steel a section of a sandwich panel was used for introducing the load in some tests (Fig. 3.5). The kind of load introduction did not have a relevant influence on the load bearing behaviour and capacity.
Fig. 3.5: Introduction of load by plate of steel and by sandwich panel

In all of the tests a local failure at the load application area occurred. The panels failed by crippling of the face sheet at the loaded free edge.

Fig. 3.6: Failure mode crippling of the face sheet

In the tests the ultimate load was determined. In the following tables the results of the tests are summarised. In addition to the ultimate load the ultimate stress in the loaded face sheet is given. The ultimate stress was determined using the measured width of the specimen and the core thickness of the face sheet.
<table>
<thead>
<tr>
<th>type of panel</th>
<th>stressed face</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>top side of production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>11,26</td>
<td>59,54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2*)</td>
<td>13,98</td>
<td>74,48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3*)</td>
<td>14,03</td>
<td>74,56</td>
</tr>
<tr>
<td></td>
<td>bottom side of production</td>
<td>4**)</td>
<td>12,53</td>
<td>66,33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5**)</td>
<td>12,11</td>
<td>64,79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6**)</td>
<td>14,58</td>
<td>78,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7**)</td>
<td>12,50</td>
<td>66,71</td>
</tr>
</tbody>
</table>

*) introduction of load by sandwich panel  
**) 2 tests performed with one specimen, test of 2nd face

Tab. 3.7: Test results – panel type A

<table>
<thead>
<tr>
<th>type of panel</th>
<th>stressed face</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td>1</td>
<td>19,24</td>
<td>63,12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>29,95</td>
<td>98,26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>21,42</td>
<td>70,45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>29,61</td>
<td>97,39</td>
</tr>
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<td></td>
<td></td>
<td>5</td>
<td>29,02</td>
<td>95,21</td>
</tr>
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<td></td>
<td></td>
<td>6</td>
<td>19,40</td>
<td>63,65</td>
</tr>
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<td></td>
<td></td>
<td>7</td>
<td>19,54</td>
<td>64,27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>21,33</td>
<td>70,16</td>
</tr>
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<td></td>
<td></td>
<td>9</td>
<td>28,01</td>
<td>92,13</td>
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<td></td>
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<td>10</td>
<td>20,33</td>
<td>66,87</td>
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<td></td>
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<td>11*)</td>
<td>15,30</td>
<td>50,32</td>
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<td></td>
<td></td>
<td>16</td>
<td>20,60</td>
<td>67,59</td>
</tr>
</tbody>
</table>

*) introduction of load by sandwich panel

Tab. 3.8: Test results – panel type B
<table>
<thead>
<tr>
<th>type of panel</th>
<th>stressed face</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>-</td>
<td>1</td>
<td>12,26</td>
<td>58,32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9,89</td>
<td>46,93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3*)</td>
<td>10,02</td>
<td>47,67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4*)</td>
<td>12,18</td>
<td>57,94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>7,18</td>
<td>34,16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6**)</td>
<td>7,89</td>
<td>37,44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7**)</td>
<td>8,26</td>
<td>39,29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8**)</td>
<td>12,26</td>
<td>58,32</td>
</tr>
</tbody>
</table>

*) introduction of load by sandwich panel
***) 2 tests performed with one specimen, test of 2nd face

Tab. 3.9: Test results – panel type C

<table>
<thead>
<tr>
<th>type of panel</th>
<th>stressed face</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>-</td>
<td>1</td>
<td>12,14</td>
<td>63,74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>12,37</td>
<td>64,94</td>
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<td></td>
<td></td>
<td>4</td>
<td>12,97</td>
<td>68,26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>12,32</td>
<td>64,68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>9,96</td>
<td>52,29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>11,50</td>
<td>60,51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>9,13</td>
<td>48,05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>8,04</td>
<td>42,32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>11,66</td>
<td>61,37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>8,71</td>
<td>45,73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>11,18</td>
<td>58,70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>10,19</td>
<td>53,63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>12,36</td>
<td>64,89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>9,12</td>
<td>47,88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>10,87</td>
<td>57,07</td>
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<td></td>
<td></td>
<td>17</td>
<td>12,76</td>
<td>67,16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>10,51</td>
<td>55,32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19*)</td>
<td>7,93</td>
<td>41,7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20*)</td>
<td>7,90</td>
<td>41,6</td>
</tr>
</tbody>
</table>

*) introduction of load by sandwich panel

Tab. 3.10: Test results – panel type E
3.3 Tests on corner details

Tests on typical corner details for the connection of wall and roof were performed. The test set up is shown in Fig. 3.7 and Fig. 3.8. To introduce the axial load into the panel a plate of steel was used. An aluminium profile was placed on the plate of steel and on an additional hinged support. The load was introduced into the profile. In addition to the applied load $F_1$ the reaction force $F_2$ at the hinged support was measured. The load introduced into the face of the panel can be calculated by subtracting $F_2$ from $F_1$.

![Test set-up](image)

**Fig. 3.7:** Test set-up

In all of the tests a local failure at the load application area occurred. The panels failed by crippling of the face sheet at the loaded free edge.

**Fig. 3.8:** Test set-up
In the following tables the results of the tests are summarised. The ultimate loads introduced into the face sheet (F₁ - F₂) and the corresponding ultimate stresses are given.

**Tab. 3.11: Test results – panel type A**

<table>
<thead>
<tr>
<th>type of panel</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>16,29</td>
<td>85,9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15,01</td>
<td>79,4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13,93</td>
<td>73,7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13,26</td>
<td>70,1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>12,63</td>
<td>66,6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17,27</td>
<td>91,5</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>16,17</td>
<td>85,5</td>
</tr>
</tbody>
</table>

**Tab. 3.12: Test results – panel type B**

<table>
<thead>
<tr>
<th>type of panel</th>
<th>number of test</th>
<th>ultimate load [kN]</th>
<th>ultimate stress [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1</td>
<td>26,28</td>
<td>86,2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>25,72</td>
<td>84,4</td>
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<td></td>
<td>3</td>
<td>25,70</td>
<td>84,3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>20,55</td>
<td>67,3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>18,43</td>
<td>60,5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>19,37</td>
<td>63,6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>20,56</td>
<td>67,4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>24,67</td>
<td>80,9</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>23,90</td>
<td>78,4</td>
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<td></td>
<td>10</td>
<td>27,80</td>
<td>91,4</td>
</tr>
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<td></td>
<td>11</td>
<td>18,86</td>
<td>61,9</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>19,88</td>
<td>65,2</td>
</tr>
</tbody>
</table>
4 Mechanical basics

4.1 Stability failure modes of a compressed face

The faces of sandwich panels consist of comparatively thin steel sheets. So they have a very high slenderness. If they are subjected to compression forces stability failure may occur. The compressed face sheet fails by a kind of buckling. So the ultimate stress of a face sheet subjected to compression is usually clearly lower than the yield strength of the face material.

At load application area the failure mode of the compressed face is crippling of the free edge. This failure mode is strongly related to wrinkling of a compressed face in mid-span.

![Crippling at load application area](image_url)
Crippling as well as wrinkling are stability failure modes. In both cases the face sheet can be regarded as a plate, which is elastically supported by the core material.

\[\sigma_{cr,w} = \frac{3}{2} \cdot \frac{\sqrt{2 \cdot c^2 \cdot EI_F}}{A_F}.\] (4.1)

The length of the buckling have waves is [15]

\[a_w = \pi \cdot \frac{\sqrt{2 \cdot EI_F}}{c}.\] (4.2)

with

stiffness of elastic foundation:

\[c = \frac{2 \cdot (1 - \nu_c)}{3 - 4 \cdot \nu_c} \cdot \sqrt{\frac{2 \cdot G_c \cdot E_c}{1 + \nu_c}}.\] (4.3)

\(EI_F\) bending stiffness of face
Formulae (4.1) and (4.2) were developed for panels with flat faces. The load bearing behaviour of lightly profiled faces is very similar to the behaviour of flat faces. Because of that (4.1) and (4.2) can also be used for lightly profiled faces [15].

If formula (4.3) is rewritten, we get for the stiffness of the elastic foundation

\[ c = A \cdot \sqrt{G_C \cdot E_C} \]  
(4.4)

A is a factor which depends only on the Poisson ratio \( \nu_C \) of the core material.

\[ A = \frac{2 \cdot (1 - \nu_C)}{3 - 4\nu_C} \cdot \sqrt{\frac{2}{1 + \nu_C}} \]  
(4.5)

In Tab. 4.1 the factor A is given for different Poisson ratio.

<table>
<thead>
<tr>
<th>( \nu_C )</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.943</td>
</tr>
<tr>
<td>0.1</td>
<td>0.934</td>
</tr>
<tr>
<td>0.2</td>
<td>0.939</td>
</tr>
<tr>
<td>0.3</td>
<td>0.965</td>
</tr>
<tr>
<td>0.4</td>
<td>1.024</td>
</tr>
<tr>
<td>0.5</td>
<td>1.155</td>
</tr>
</tbody>
</table>

Tab. 4.1: Relation of Poisson ratio and factor A of formula (4.5)

For core materials as polyurethane or expanded polystyrene the Poisson ratio is between 0.0 and 0.3. For these values the influence of the Poisson ratio on the factor A is very small (approx. 2%). Therefore also the influence on the stiffness c of the elastic foundation and consequently on the length of the buckling waves and on the elastic buckling stress of the face is very small. In the following for the core material a Poisson ratio \( \nu_C = 0 \) is assumed.

With this assumption we get for the stiffness of the elastic foundation

\[ c = \frac{2}{3} \cdot \sqrt{2 \cdot G_C \cdot E_C} \]  
(4.6)

With the stiffness c given above the elastic buckling stress and the length of the buckling half wave are
\[
\sigma_{cr,w} = \frac{3}{A_F} \sqrt{\frac{2}{9} \cdot EI_F \cdot G_C \cdot E_C}
\]  \hspace{1cm} (4.7)

\[
a_w = \pi \sqrt{\frac{9 \cdot EI_F^2}{2 \cdot G_C \cdot E_C}}
\]  \hspace{1cm} (4.8)

For panels with flat face sheets the following formulae can be inserted in (4.7) and (4.8).

\[
A_F = t_F
\]  \hspace{1cm} (4.9)

\[
EI_F = E_F \cdot \frac{t_F^3}{12 \cdot (1 - \nu_F^2)}
\]  \hspace{1cm} (4.10)

With \( \nu_F = 0.3 \) (steel) for plane faces the elastic buckling stress and the length of the buckling half waves are

\[
\sigma_{cr,w} = 3 \cdot \frac{2}{3} \sqrt{\frac{E_F}{12 \cdot (1 - \nu_F^2)}} \cdot G_C \cdot E_C = 0.82 \cdot \sqrt{E_F \cdot G_C \cdot E_C}
\]  \hspace{1cm} (4.11)

\[
a_w = \pi \cdot t_F \cdot \sqrt{\frac{9 \cdot E_F^2}{2 \cdot G_C \cdot E_C \cdot (12 \cdot (1 - \nu_F^2))^2}} = 1.82 \cdot t_F \cdot \sqrt{\frac{E_F^2}{G_C \cdot E_C}}
\]  \hspace{1cm} (4.12)

The slenderness of a compressed component is calculated by the following formulae [6].

\[
\lambda = \sqrt{\frac{A \cdot f_y}{N_{cr}}}
\]  \hspace{1cm} (4.13)

Based on this the slenderness of the elastically supported infinite face is

\[
\lambda_w = \sqrt{\frac{f_{y,F}}{\sigma_{cr,w}}}
\]  \hspace{1cm} (4.14)

At the load application area the normal force is introduced into the free edge of the face. So the face corresponds to a semi-infinitely elastically supported plate. Only one end of the plate is supported; the other one is free.

From the theory of beams on elastic foundation the following elastic buckling loads are known [9], [10].

For an infinite beam (both ends supported) the elastic buckling load is

\[
N_{cr} = 2 \cdot \sqrt{k \cdot EI}
\]  \hspace{1cm} (4.15)

with

\[ k \]  \hspace{1cm} stiffness of elastic foundation

For a semi-infinite beam (free end) the elastic buckling load is half of the load of the infinite beam.
Analogously the elastic buckling stress of a semi-infinite plate on an elastic foundation (crippling of free edge) is

$$\sigma_{cr,e} = \frac{1}{2} \cdot \sigma_{cr,w}$$  \hspace{1cm} (4.17)

With the simplification $v_C = 0$ introduced above the elastic buckling stress of the free edge is

$$\sigma_{cr,e} = \frac{3}{2 \cdot A_F} \cdot \sqrt{\frac{2}{9} \cdot E_I F \cdot G_C \cdot E_C}$$  \hspace{1cm} (4.18)

For plane faces we get the following elastic buckling stress

$$\sigma_{cr,e} = 0.41 \cdot \sqrt{E_I F \cdot G_C \cdot E_C}$$  \hspace{1cm} (4.19)

The slenderness of the semi-infinite plate on an elastic foundation is

$$\lambda_c = \sqrt{\frac{f_{y,F}}{\sigma_{cr,e}}} = \sqrt{\frac{1}{2} \cdot \frac{f_{y,F}}{\sigma_{cr,w}}} = \sqrt{2} \cdot \lambda_w$$  \hspace{1cm} (4.20)

The buckling length of the semi-infinite plate is (for $v_C = 0$)

$$a_c = \sqrt{2} \cdot a_w = \sqrt{2} \cdot \pi \cdot \sqrt{\frac{9 \cdot B_F^2}{2 \cdot G_C \cdot E_C}}$$  \hspace{1cm} (4.21)

For plane faces the buckling length can be simplified to

$$a_c = 2.574 \cdot t_F \cdot \sqrt{\frac{E_F^2}{G_C \cdot E_C}}$$  \hspace{1cm} (4.22)

4.3 Buckling loads for local buckling of the face

If the ultimate load of a compressed component is determined by testing, it usually differs clearly from the elastic buckling load. This is caused by geometrical and material non-linearity as well as by different imperfections, which may influence the load bearing capacity. These effects can be considered by a calculation according to $2^{nd}$ order theory. In this calculation initial deformations have to be taken into account as imperfections. To cover all imperfections (e.g. initial deformations, material imperfections, residual stresses) an equivalent geometrical imperfection can be used [6]. An initial deformation is considered, which has the same effects as the real imperfections. For the initial deformation the most disadvantageous shape has to be used. This is usually the first eigenmode. To determine the wrinkling or crippling stress of
the compressed face of a sandwich panel, as geometrical imperfection an initial deformation of the face is assumed. The initial deformation corresponds to the first eigenmode of wrinkling in mid-span or crippling of the free edge respectively. Alternatively to a calculation by 2\textsuperscript{nd} order theory a calculation by the equivalent member method with buckling curves can be performed to determine the buckling load of a compressed member [6]. Depending on the slenderness of the component a reduction factor is determined. With the reduction factor the yield strength is reduced to the buckling stress.

\[ \sigma_{w/c} = \chi \cdot f_y \]  

(4.23)

The reduction factor is determined as follows

\[ \chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \leq 1 \]  

(4.24)

\[ \phi = \frac{1}{2} \cdot \left( 1 + \alpha \cdot (\lambda - \lambda_0) + \lambda^2 \right) \]  

(4.25)

The slenderness \( \lambda_0 \) is a plateau value. If the slenderness of a component is less than \( \lambda_0 \) the yield strength is not reduced. According to EN 1993-1-1 for steel sections \( \lambda_0 = 0,2 \) has to be used.

---

Fig. 4.5: Buckling curves [6]
In addition to the slenderness of the considered member the reduction factor depends on the imperfection factor \( \alpha \). Analogous to the equivalent geometrical imperfection this imperfection factor covers different imperfections (e.g. initial deformations, material imperfections, residual stresses). In EN 1993-1-1 the following imperfection factors are given for the different buckling curves.

<table>
<thead>
<tr>
<th>buckling curve</th>
<th>imperfection factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.21</td>
</tr>
<tr>
<td>b</td>
<td>0.34</td>
</tr>
<tr>
<td>c</td>
<td>0.49</td>
</tr>
<tr>
<td>d</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Fig. 4.6: Imperfection factors according to EN 1993-1-1

At load application areas there are additional imperfections, which mainly develop through sawing of the cut in the wall panel. During sawing often cracks occur between core and face, which disturb the bonding between core and face. Uneven cut edges result in contact imperfections and thus in stress peaks at the load application area (Fig. 4.7 and Fig. 4.8). This imperfections result in a further decrease of the load bearing capacity of the free edge.

Fig. 4.7: Cracks between core and face and uneven cut edge

Fig. 4.8: Uneven cut edge
5 FE-models of numerical calculations

5.1 General

To investigate the load bearing behaviour and capacity of the load application area numerical calculations have been performed. The finite element program ANSYS has been used.

The face sheets of the panel were modelled with shell elements of type Shell 181. This element is defined by four nodes with three displacement degrees of freedom and three rotational degrees of freedom. It has bending, membrane and shear stiffness. As material behaviour, bilinear material equations were arranged (linear-elastic, ideal-plastic), i.e. after reaching the yield strength, yielding occurs without strain hardening.

The core layer of the panel was represented by volume elements of type Solid 185. This element has eight nodes with three displacement degrees of freedom. For the numerical investigations homogenous and isotropic core material was assumed.

As first step of the numerical calculation a linear buckling analysis is performed. As results of this analysis we get eigenvalue (elastic buckling load) and eigenmode. After the linear buckling analysis a non-linear analysis is performed to determine the load bearing capacity. In this analysis geometrical and material non-linearities are considered. So initial deformations must be taken into account. As initial deformation the first eigenmode determined in the linear buckling analysis is used.

5.2 Wrinkling in mid-span

To have reference values some investigations on the wrinkling stress in mid-span (face with infinite length) were performed. The model used for these calculations consists of a face sheet, which is supported by the core material. For sufficient thick panels both face sheets are independent of each other. So it is sufficient to represent only one face in the numerical model. The thickness of the core material has to be chosen as high that the deformations are gone down at the side opposite to the loaded face. The face is loaded by a normal force.

To take advantage of the symmetry only half of the model is represented in the FE-model. At one transverse edge symmetrical boundary conditions are used. Also at the longitudinal edges the model has symmetrical boundary conditions. At the side opposite to the loaded face the core is supported in thickness direction. The loaded edge of the face is supported in thickness direction and rotations are restraint. Because of the clamped edge failure occurs in mid-span. In the following figures transverse and longitudinal section of the model are shown.
Depending on the stiffness of face and core the length of the buckling waves, which cause the lowest eigenvalue, differs. To make sure that this buckling length can occur, for each model an appropriate length has to be chosen. For the calculations in the report at hand the length of the model was six times the length of a buckling wave according to formula (4.8).
5.3 Crippling at load-application area

Like the model for calculation of the wrinkling stress in mid-span the model for investigations on the crippling stress consists of a face sheet, which is supported by the core material. In contrast to the model given in the previous section the loaded edge is not supported. The normal force is introduced into a free edge.

For sufficient long models there is no influence of the length L on the load bearing behaviour and capacity of the loaded edge. So in a preliminary investigation the length of the model has
been chosen in a way that there is no influence of the length on the load bearing capacity of the edge. The face can be regarded as a semi-infinite plate.

![Graph showing the influence of length of the model on buckling load](image)

**Fig. 5.5:** Influence of length of the model on buckling load
6 Wrinkling stress in mid-span

6.1 Introduction

To have a reference value some investigations on the wrinkling stress in mid-span have been performed. For the numerical investigations the FE-model described in section 5.2 has been used. As imperfection the first eigenmode, which was determined in an elastic buckling analysis, was used. The amplitude of the pre-deformation has been chosen approximately according to the acceptable deviation from flatness according to section D.2.2 of EN 14509. According to EN 14509 the deviation from flatness has to be lower than the following values:

<table>
<thead>
<tr>
<th>measuring length</th>
<th>acceptable deviation from flatness</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>400 mm</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>700 mm</td>
<td>1.5 mm</td>
</tr>
</tbody>
</table>

Tab. 6.1: Acceptable deviation from flatness according to EN 14509

If these values are converted in amplitudes per length $a_w$ of a buckling wave (cf. Fig. 6.1), we get as imperfections $a_w/176$, $a_w/200$ and $a_w/233$. 
According to the buckling curves of EN 1993-1-1 the following pre-deformations have to be used.

<table>
<thead>
<tr>
<th>buckling curve</th>
<th>pre-deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>L/300</td>
</tr>
<tr>
<td>b</td>
<td>L/250</td>
</tr>
<tr>
<td>c</td>
<td>L/200</td>
</tr>
<tr>
<td>d</td>
<td>L/150</td>
</tr>
</tbody>
</table>

The pre-deformations according to buckling curve b, c and d approximately correspond to the acceptable deviations from flatness given in EN 14509. So these values have been chosen for the following investigations.

6.2 Numerical investigations

By numerical calculations the ultimate stress (wrinkling stress) was determined. Within the calculations the thickness and the yield strength of the face and the material parameters of the core were varied. So the wrinkling stress $\sigma_w$ was determined for different slenderness's. Based on the wrinkling stress $\sigma_w$, which was numerically determined, the reduction factor was determined.

$$\chi_w = \frac{\sigma_w}{f_{y,F}} \leq 1$$

(6.1)

In the following diagram the reduction factors are given as a function of the slenderness of the face. All parameters used for the calculations as well as the results are given in Annex 1.
In the following figures the results of the numerical calculations are compared to the buckling curves according to EN 1993-1-1 (blue curves). The buckling curves have been adjusted to have curves, which fit to the results of the numerical calculation (black curves). This has been done by an adjustment of the slenderness $\lambda_0$ to 0,7.
Fig. 6.3: Buckling curves for L/150

Fig. 6.4: Buckling curves for L/200
In several publications [12], [13] for the faces of sandwich panels with polyurethane foam core a pre-deformation of $a_w/500$ is suggested as a realistic value. Therefore for this imperfection numerical calculations have been performed and the imperfection factor $\alpha$ has been determined. It was assumed that the slenderness $\lambda_0$ is a constant value and thus can also be used for this case. The imperfection factor $\alpha = 0.21$ was determined. In the following diagram the results of the numerical calculation and the corresponding buckling curve are presented.

Fig. 6.5: Buckling curves for L/250
6.3 Conclusion

So if the imperfection factor for the considered panel would be known, the wrinkling stress of a flat or lightly profiled sandwich panel could be determined by calculation using buckling curves. In dependence of the equivalent geometrical imperfection (pre-deformation) the imperfection factors given in EN 1993-1-1 can be used. For a pre-deformation of L/500, which is according to [12] and [13] a realistic value for the face of a sandwich panel with a core made of polyurethane, the imperfection factor $\alpha = 0.21$ can be used. In comparison to EN 1993-1-1 the slenderness $\lambda_0$ was adjusted to $\lambda_0 = 0.7$.

To use buckling curves for determination of the wrinkling stress by calculation, the imperfection factor $\alpha$ of the considered panel would need to be known. This factor depends on imperfections resulting from the production process as well as on the quality of the bond between core and face. So the imperfection factor should be determined by tests, i.e. the wrinkling stress is determined by testing and subsequently the imperfection factor is recalculated using formula (6.2). In the following this factor will be used to consider imperfections and quality of the bond between core and face also for the determination of the crippling stress of a free edge.

$$\alpha = \frac{1 + \chi_w \cdot \lambda_w^2 \cdot \left(\chi_w - 1\right) - \chi_w}{\chi_w \cdot \left(\lambda_w - \lambda_0\right)} \geq 0.21$$ (6.2)
7 Crippling of free edge

Numerical calculations have been performed to determine the crippling stress of a free edge, which is subjected to compression forces. The model described in section 5.3 has been used. As for the investigations on wrinkling in mid-span the first eigenmode, which was determined by an elastic buckling analysis, was used as geometrical imperfection. The same initial deformations have been chosen as for the investigations on the wrinkling stress in mid-span (L/150, L/200, L/250 and L/500). In the numerical calculation the ultimate stress and based on this the reduction factor was determined. All parameters used for the calculations as well as the results are given in Annex 2. The reduction factors determined by numerical calculations are compared to the buckling curves determined in the previous section (Fig. 7.1 to Fig. 7.4).

![Fig. 7.1: Numerical results and buckling curve for L/150](image-url)
Fig. 7.2: Numerical results and buckling curve for L/200

Fig. 7.3: Numerical results and buckling curve for L/250
The buckling curves determined for calculation of wrinkling stress in mid-span are also suitable for determination of the crippling stress of a free edge.

In addition to the imperfections, which are considered in the buckling curve by the imperfection factor \( \alpha \), at the free edge there are additional imperfections. From sawing of the edge cracks between core and face may occur. If the cut edge is uneven, the load is not introduced constantly over the width of the panel. Both things may decrease the load bearing capacity of the load application area. The influence of these further imperfections is investigated in the following section.

### 8 Consideration of further imperfections

If the load bearing capacity of a load application detail is determined by calculation with buckling curves (cf. section 7) an equivalent pre-deformation of the face is considered. This includes only the imperfections, which are also available in mid-span of the panel. Further imperfections as cracks between core and face and uneven cut edges cause an additional decrease of the load bearing capacity. This was investigated by evaluation of the tests, which are described in section 3. Because both kinds of test (direct introduction of the load and tests on corner details) showed no significant difference of the load bearing capacity, in the following all results are evaluated together.

To determine the influence of the imperfections caused by sawing of the edge the load bearing capacity of a panel without these imperfections must be known. The ultimate stress of a
panel with a perfect cut edge can be determined by the buckling curves given above. But to use the buckling curves the imperfection factor $\alpha$ for the considered panel must be known.

To determine the imperfection factor the wrinkling stress determined by tests (cf. Tab. 3.5) is used. From this wrinkling stress the imperfection factor was recalculated (Tab. 8.1). In doing so the mean value of the wrinkling stresses determined for one type of panel was used. Also for the other material factors the mean values determined by tests have been used. For some panels the calculated imperfection factor is lower than 0.21, what corresponds to an imperfection of L/500. In these cases the imperfections factor $\alpha = 0.21$ was used as a minimum value.

<table>
<thead>
<tr>
<th>type of panel</th>
<th>wrinkling stress (mean values) [N/mm²]</th>
<th>yield strength [N/mm²]</th>
<th>reduction factor</th>
<th>slenderness $\lambda_w$ of the face</th>
<th>imperfection factor $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>201</td>
<td>358</td>
<td>0.561</td>
<td>1.311</td>
<td>$\leq 0.21$</td>
</tr>
<tr>
<td>B</td>
<td>201</td>
<td>403</td>
<td>0.499</td>
<td>1.446</td>
<td>$\leq 0.21$</td>
</tr>
<tr>
<td>C</td>
<td>176</td>
<td>409</td>
<td>0.430</td>
<td>1.600</td>
<td>$\leq 0.21$</td>
</tr>
<tr>
<td>E</td>
<td>196</td>
<td>467</td>
<td>0.281</td>
<td>1.253</td>
<td>2.60</td>
</tr>
</tbody>
</table>

Details of determination of the imperfection factor are given in Annex 3.

Tab. 8.1: Imperfection factors determined from wrinkling tests

With the imperfection factor determined from the wrinkling stress in mid-span the crippling stress $\sigma_{c*}$ of the free edge is calculated (Tab. 8.2). These calculated values consider only the imperfections, which are also available at mid-span; they require a perfect cut edge. Further imperfections, which are caused by cutting of the edge (e.g. contact imperfections), are not considered.

<table>
<thead>
<tr>
<th>type of panel</th>
<th>yield strength [N/mm²]</th>
<th>imperfection factor $\alpha$</th>
<th>slenderness $\lambda_c$ of the face</th>
<th>reduction factor</th>
<th>crippling stress $\sigma_{c*}$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>358</td>
<td>0.21</td>
<td>1.854</td>
<td>0.265</td>
<td>95.0</td>
</tr>
<tr>
<td>B</td>
<td>403</td>
<td>0.21</td>
<td>2.044</td>
<td>0.220</td>
<td>88.7</td>
</tr>
<tr>
<td>C</td>
<td>409</td>
<td>0.21</td>
<td>2.262</td>
<td>0.181</td>
<td>74.1</td>
</tr>
<tr>
<td>E</td>
<td>467</td>
<td>2.60</td>
<td>1.772</td>
<td>0.155</td>
<td>72.6</td>
</tr>
</tbody>
</table>

Details of determination of the crippling stress $\sigma_{c*}$ are given in Annex 3.

Tab. 8.2: Crippling stresses

To evaluate the influence of additional imperfections, which are caused by cutting of the edge and therefore are only available at the load application area, the calculated values of the crippling stress $\sigma_{c*}$ (Tab. 8.2) are compared to the ultimate stresses determined in the tests. In some tests the ultimate stress was in the range of or even slightly higher than the elastic buckling stress. These results were not taken into account in the evaluation of the tests. In
Tab. 8.3 for each test the reduction factor \(\frac{\sigma_{c,\text{test}}}{\sigma_{c,\text{cal}}^*}\) is determined. In doing so the crippling stresses (local buckling of a free edge) determined in the tests (Tab. 3.7 to Tab. 3.14) are divided by the respective calculated values \(\sigma_{c}^*\) given in Tab. 8.2. This reduction factor describes the decrease of the load bearing capacity caused by imperfections resulting from cutting of the edge. By a statistical evaluation the characteristic value of the reduction factor was determined to \(\sigma_{c,\text{test}}/\sigma_{c,\text{cal}} = 0.54\).

<table>
<thead>
<tr>
<th>panel type A</th>
<th>panel type B</th>
<th>panel type C</th>
<th>panel type E</th>
</tr>
</thead>
<tbody>
<tr>
<td>ultimate stress (tests) ([\text{N/mm}^2])</td>
<td>(\sigma_{c,\text{test}}/\sigma_{c,\text{cal}})</td>
<td>ultimate stress (tests) ([\text{N/mm}^2])</td>
<td>(\sigma_{c,\text{test}}/\sigma_{c,\text{cal}})</td>
</tr>
<tr>
<td>59.5</td>
<td>0.627</td>
<td>63.1</td>
<td>0.712</td>
</tr>
<tr>
<td>74.5</td>
<td>0.784</td>
<td>70.5</td>
<td>0.794</td>
</tr>
<tr>
<td>74.6</td>
<td>0.785</td>
<td>63.7</td>
<td>0.718</td>
</tr>
<tr>
<td>66.5</td>
<td>0.700</td>
<td>64.3</td>
<td>0.725</td>
</tr>
<tr>
<td>64.8</td>
<td>0.682</td>
<td>70.2</td>
<td>0.791</td>
</tr>
<tr>
<td>78.0</td>
<td>0.821</td>
<td>92.1</td>
<td>1.039</td>
</tr>
<tr>
<td>66.7</td>
<td>0.702</td>
<td>66.9</td>
<td>0.754</td>
</tr>
<tr>
<td>85.9</td>
<td>0.904</td>
<td>50.3</td>
<td>0.567</td>
</tr>
<tr>
<td>79.4</td>
<td>0.836</td>
<td>53.2</td>
<td>0.599</td>
</tr>
<tr>
<td>73.7</td>
<td>0.776</td>
<td>48.6</td>
<td>0.548</td>
</tr>
<tr>
<td>57.1</td>
<td>0.738</td>
<td>66.1</td>
<td>0.746</td>
</tr>
<tr>
<td>66.6</td>
<td>0.701</td>
<td>79.2</td>
<td>0.893</td>
</tr>
<tr>
<td>91.5</td>
<td>0.963</td>
<td>67.6</td>
<td>0.762</td>
</tr>
<tr>
<td>85.5</td>
<td>0.900</td>
<td>86.2</td>
<td>0.972</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{mean value of } & \sigma_{c,\text{test}}/\sigma_{c,\text{cal}} = 0.75 \\
\text{characteristic value of } & \sigma_{c,\text{test}}/\sigma_{c,\text{cal}} = 0.54
\end{align*}
\]
So to determine the crippling stress of the free edge the imperfection factor $\alpha$ of the panel has to be known. This factor is determined based on the wrinkling stress in mid-span (cf. formula (6.2)). (To determine the wrinkling stress tests are necessary.) With the imperfection factor the crippling stress $\sigma_{c}^{*}$ of a perfectly cut edge is determined by buckling curves (formulae (4.24) and (4.25)). To consider further imperfection, which are caused by cutting of the edge, the crippling stress has to be decreased by the factor 0,54 to get the characteristic value or by 0,75 to get the mean value. In Fig. 8.1 for panel type E the crippling stresses determined by tests are compared to the calculated values.

![Comparison of tests results and calculated values](image)

**Fig. 8.1:** Comparison of tests results and calculated values

Obviously imperfections caused by cutting of the edge reduce the load bearing capacity of the load application area significantly. So if sandwich panels are intended to introduce normal forces into the free edges of the face, special care should be taken, when cutting the panel. It should be avoided to damage the edges of the panel, i.e. the bond between core and face should not be destroyed. Furthermore it is important to have even cut edges to be able to introduce the loads constantly over the width of the panel.

### 9 Introduction of loads in both face sheets

In the tests and also in the numerical calculations the load was applied to one face of a sandwich panel only. But in practice there are also applications, which require applying loads to both faces of a panel, e.g. the roof introduces loads into an interior wall. For panels with a
sufficiently thick core (approx. 60 mm) both faces do not influence each other [15]. This is also shown by the tests on load application areas presented in section 3.2. For some samples both faces were tested one after the other. The results of the tests on samples with one face already destructed do not differ significantly from the tests on “new” samples. The independent behaviour of both faces could also be shown with an additional test series. For these tests sandwich panels with a mineral wool core with thickness 60 mm have been used. Two tests with introduction of the load into both faces and two tests with introduction of the load into one face only have been performed (Fig. 9.1).

![Introduction of load into both faces and into one face](image)

*Fig. 9.1: Introduction of load into both faces and into one face*

The results of the tests (ultimate loads) are given in Tab. 9.1.

<table>
<thead>
<tr>
<th>Introduction into both faces</th>
<th>Introduction into one face</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>13.9 kN</td>
</tr>
<tr>
<td>No. 2</td>
<td>13.7 kN</td>
</tr>
<tr>
<td>No. 3</td>
<td>6.9 kN</td>
</tr>
<tr>
<td>No. 4</td>
<td>6.8 kN</td>
</tr>
</tbody>
</table>

*Tab. 9.1: Ultimate loads*

The results of test no. 3 and 4 (introduction of load into one face) are approximately half of the values of test no. 1 and 2 (introduction of load into both faces). So obviously, both faces do not depend from each other. For panels with loading of both faces a reduction of the load bearing capacity is not necessary.
10 Design of load application areas

To design the load application area of an axially loaded sandwich panel, where normal forces are introduced into the free edge of the panel, the following calculation procedure can be used.

The basis of the calculations is the wrinkling stress in mid-span. The wrinkling stress is determined by testing. Usually it can be found on the CE-mark of the sandwich panel or in approvals. Based on the wrinkling stress the imperfection factor \( \alpha \) of the considered panel is calculated. As a minimum value \( \alpha = 0.21 \) is used.

\[
\alpha = \frac{1 + \chi_w \cdot \lambda_w^2 \cdot (\chi_w - 1) - \chi_w \cdot (\lambda_w - \lambda_0)}{\chi_w \cdot (\lambda_w - \lambda_0)} \geq 0.21
\] (10.1)

with

reduction factor for wrinkling stress:

\[
\chi_w = \frac{\sigma_{w}}{f_{y,F}}
\] (10.2)

elastic buckling load (wrinkling):

\[
\sigma_{cr,w} = \frac{3}{A_P} \sqrt{\frac{2}{9} \cdot EI_f \cdot G_C \cdot E_C}
\] (10.3)

slenderness for wrinkling:

\[
\lambda_w = \sqrt{\frac{f_{y,F}}{\sigma_{cr,w}}}
\] (10.4)

\[
\lambda_0 = 0.7
\] (10.5)

With the imperfection factor the crippling stress \( \sigma^*_c \) of the free edge is determined. This value only considers imperfections, which are available at the free edge as well as at mid-span. Further imperfections of the free edge, e.g. contact imperfections, are not considered.

\[
\sigma^*_c = \chi_c \cdot f_{y,F}
\] (10.6)

with

slenderness for crippling

\[
\lambda_c = \sqrt{2} \cdot \lambda_w
\] (10.7)

reduction factor for crippling stress

\[
\chi_c = \frac{1}{\phi + \sqrt{\phi^2 - \lambda_c^2}} \leq 1
\] (10.8)

\[
\phi = \frac{1}{2} \left( 1 + \alpha \cdot (\lambda_c - \lambda_0) + \lambda_c^2 \right)
\] (10.9)
To consider also further imperfections of the free edge, e.g. uneven cut edges, which can cause contact imperfections, an additional reduction of the crippling stress has to be taken into account. From the stress $\sigma_c^*$ the characteristic value of the crippling stress is calculated to

$$\sigma_{c,k} = 0.54 \cdot \sigma_c^*$$

(10.10)

To design the load application area the crippling stress has to be compared to the introduced normal stress $\sigma_d$.

$$\sigma_d \leq \frac{\sigma_{c,k}}{\gamma_M}$$

(10.11)

The introduced stress $\sigma_d$ is a design value. By determination of this value load factors $\gamma_F$ and combination coefficients $\Psi$ have to be considered. They are given by national specifications, e.g. they can be found in EN 1990 [5] and the related national annex.

For sandwich panels the material factors $\gamma_M$ represent the variability of the mechanical properties of the sandwich panel. They are determined by the results of initial type testing and factory production control. Because the failure mode of crippling of the free edge is related to wrinkling in mid-span, the material factors for wrinkling could also be used for the design of load application areas.

11 Load application details with glued cores

Especially for cooling chambers it is common practice to glue the cores of the panel at the connection between roof and wall. To investigate the influence of this additional connection tests on corner details with glued cores have been performed. A wall panel and a roof panel of the same type were glued with glue „OTTOCOLL® P84“ (polyurethane glue). The roof panel was loaded as single span beam. The test set up of the tests is shown in Fig. 11.1 and Fig. 11.2. The roof panel was supported by an additional hinged support and loaded by four line loads. During the test the reaction force $F_2$ at the hinged support and the deflection in mid-span at the lower face of the panel were measured.
Fig. 11.1: Test set-up

In all tests failure did not occur in the wall but in the roof panel.
Fig. 11.3: Failure of roof panels

In the following table the results of the tests are summarised. The ultimate load $F_1$ (load introduced into roof panel) and $F_2$ (load at support) and the quotient of both values are given. The load-deflection curves of the tests are presented in Fig. 11.4 to Fig. 11.7.

<table>
<thead>
<tr>
<th>type of panel</th>
<th>number of test</th>
<th>$F_1$ [kN]</th>
<th>$F_2$ [kN]</th>
<th>$F_2/F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>8,72</td>
<td>4,36</td>
<td>0,50</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10,79</td>
<td>5,50</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9,77</td>
<td>4,96</td>
<td>0,51</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>16,07</td>
<td>8,22</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15,44</td>
<td>7,72</td>
<td>0,50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>14,09</td>
<td>7,17</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>15,59</td>
<td>7,94</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>15,29</td>
<td>7,88</td>
<td>0,52</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>16,11</td>
<td>8,39</td>
<td>0,52</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>8,34</td>
<td>3,99</td>
<td>0,48</td>
</tr>
</tbody>
</table>

Tab. 11.1: Test results
Fig. 11.4: Load-deflection curve – panel type A

Fig. 11.5: Load-deflection curve – panel type B (test 1-3)
If the load introduced into the roof panel and the force measured at the support are compared, it is obvious that half of the load is transferred to the hinged support and half of the load to the...
inner face of the wall panel. So the connection between wall and roof can be regarded as hinged, no moments are transferred, even if the cores of wall and roof panel are bonded by gluing. The load from the roof is applied as normal force into the inner face of the wall panel.

Fig. 11.8: Static system of connection between wall and roof

12 Summary

The common application of sandwich panels is enclosure of buildings. A new application is to apply sandwich panels without any load transferring substructure. In this new type of application the sandwich panels have to transfer loads and to stabilise the building. The wall panels transfer normal forces arising from the superimposed load from overlying roof or ceiling panels.

Within the framework of work package 3 of the EASIE project, design methods for axially loaded sandwich panels have been developed. In addition to the global load bearing behaviour [1] also the load application area, e.g. the connection between wall and roof, where normal forces are introduced by contact, has to be considered. In the report at hand a design procedure for the load application area of axially loaded sandwich panels is introduced. Based on the wrinkling stress in mid-span the ultimate stress of the load application area can be determined. The method has the advantage, that only values, which are also used to design sandwich panels subjected to bending loads, are needed. So to be able to design a panel for axial loads no additional tests have to be performed. Only the usual tests according to EN 14509 are needed.
13 References


## Results of numerical investigations - wrinkling in mid-span

<table>
<thead>
<tr>
<th>No.</th>
<th>$t_F$ [mm]</th>
<th>$f_{y,F}$ [N/mm²]</th>
<th>$E_C$ [N/mm²]</th>
<th>$G_C$ [N/mm²]</th>
<th>$\sigma_{cr,w}$ [N/mm²]</th>
<th>$\lambda_w$</th>
<th>$a_w$ [mm]</th>
<th>pre-deformation</th>
<th>$\sigma_{ult}$ (FE) [N/mm²]</th>
<th>reduction factor (FE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,5</td>
<td>150</td>
<td>24</td>
<td>12</td>
<td>322</td>
<td>0,683</td>
<td>21,05</td>
<td>a/150</td>
<td>159,7</td>
<td>1,064</td>
</tr>
<tr>
<td>2</td>
<td>0,5</td>
<td>150</td>
<td>16</td>
<td>8</td>
<td>246</td>
<td>0,781</td>
<td>24,09</td>
<td>a/150</td>
<td>135,2</td>
<td>0,901</td>
</tr>
<tr>
<td>3</td>
<td>0,5</td>
<td>200</td>
<td>14</td>
<td>7</td>
<td>225</td>
<td>0,943</td>
<td>25,19</td>
<td>a/150</td>
<td>138,9</td>
<td>0,694</td>
</tr>
<tr>
<td>4</td>
<td>0,5</td>
<td>200</td>
<td>8</td>
<td>4</td>
<td>155</td>
<td>1,137</td>
<td>30,36</td>
<td>a/150</td>
<td>103,5</td>
<td>0,517</td>
</tr>
<tr>
<td>5</td>
<td>0,5</td>
<td>200</td>
<td>6</td>
<td>3</td>
<td>128</td>
<td>1,251</td>
<td>33,41</td>
<td>a/150</td>
<td>90,4</td>
<td>0,452</td>
</tr>
<tr>
<td>6</td>
<td>0,5</td>
<td>360</td>
<td>8</td>
<td>4</td>
<td>155</td>
<td>1,525</td>
<td>30,36</td>
<td>a/150</td>
<td>125,2</td>
<td>0,348</td>
</tr>
<tr>
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<td>240</td>
<td>4</td>
<td>2</td>
<td>97</td>
<td>1,569</td>
<td>38,25</td>
<td>a/150</td>
<td>75,8</td>
<td>0,316</td>
</tr>
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<td>8</td>
<td>0,5</td>
<td>360</td>
<td>6</td>
<td>3</td>
<td>128</td>
<td>1,679</td>
<td>33,41</td>
<td>a/150</td>
<td>105,7</td>
<td>0,294</td>
</tr>
<tr>
<td>9</td>
<td>0,5</td>
<td>360</td>
<td>4</td>
<td>2</td>
<td>97</td>
<td>1,922</td>
<td>38,25</td>
<td>a/150</td>
<td>83,2</td>
<td>0,231</td>
</tr>
<tr>
<td>10</td>
<td>0,5</td>
<td>400</td>
<td>4</td>
<td>2</td>
<td>97</td>
<td>2,026</td>
<td>38,25</td>
<td>a/150</td>
<td>84,9</td>
<td>0,212</td>
</tr>
<tr>
<td>11</td>
<td>0,5</td>
<td>360</td>
<td>2</td>
<td>1</td>
<td>61</td>
<td>2,421</td>
<td>48,19</td>
<td>a/150</td>
<td>54,6</td>
<td>0,152</td>
</tr>
<tr>
<td>12</td>
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<td>150</td>
<td>24</td>
<td>12</td>
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Annex 2.2 of report
No.: D3.3 – part 5

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<th>\lambda_c</th>
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<th>\sigma_{\sigma_{\text{ult}}} (FE) [N/mm²]</th>
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Slenderness of faces of panels used for the tests – wrinkling in mid-span

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<th>$E_C$ [N/mm$^2$]</th>
<th>$G_C$ [N/mm$^2$]</th>
<th>$f_{y,F}$ [N/mm$^2$]</th>
<th>$EI_F$ [Nmm$^2$/mm]</th>
<th>$A_F$ [mm$^2$/mm]</th>
<th>$\sigma_{cr,w}$ $^1)$ [N/mm$^2$]</th>
<th>$\lambda_w$ $^2)$</th>
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$^1)$ elastic buckling load for wrinkling of face in mid-span

$$\sigma_{cr,w} = \frac{3}{A_F} \cdot \sqrt{\frac{2}{9} \cdot EI_F \cdot G_C \cdot E_C}$$

$^2)$ slenderness of face (wrinkling in mid-span)

$$\lambda_w = \sqrt{\frac{f_{y,F}}{\sigma_{cr,w}}}$$

Imperfection factor $\alpha$ of panels used for the tests

<table>
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<tr>
<th>type of panel</th>
<th>wrinkling stress $\sigma_w$ (mean values) [N/mm$^2$]</th>
<th>$f_{y,F}$ [N/mm$^2$]</th>
<th>reduction factor $^3)$</th>
<th>slenderness $\lambda_w$ $^2)$ of the face</th>
<th>imperfection factor $\alpha$ $^4)$</th>
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$^3)$ reduction factor for wrinkling

$$\chi_w = \frac{\sigma_w}{f_{y,F}}$$

$^4)$ imperfection factor

$$\alpha = \frac{1 + \chi_w \cdot \lambda_w^2 \cdot (\chi_w - 1) - \chi}{\chi_w \cdot (\lambda_w - \lambda_0)} \geq 0,21$$
Slenderness of faces of panels used for the tests – crippling of a free edge

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<th>$G_C$ [N/mm$^2$]</th>
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<th>$EI_F$ [Nmm$^2$/mm]</th>
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5) elastic buckling load for crippling of a free edge

$$\sigma_{cr,c} = \frac{3}{2} \cdot \frac{1}{A_F} \cdot \sqrt{\frac{2}{9} \cdot EI_F \cdot G_C \cdot E_C}$$

6) slenderness of face (crippling of a free edge)

$$\lambda_c = \sqrt{\frac{f_{y,F}}{\sigma_{cr,c}}}$$

Crippling stress $\sigma_c^*$ of panels used for the tests

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7) reduction factor for crippling of free edge

$$\chi_c = \frac{1}{\phi + \sqrt{\phi^2 - \lambda_c^2}} \leq 1$$

$$\phi = \frac{1}{2} \cdot (1 + \alpha \cdot (\lambda_c - \lambda_0) + \lambda_c^2); \quad \lambda_0 = 0,7$$

8) crippling stress $\sigma_c^*$

$$\sigma_c^* = \chi_c \cdot f_{y,F}$$