easie

Ensuring Advancement in Sandwich Construction Through Innovation and Exploitation

2008 October
2011 September

RESEARCH RESULTS

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Facilitate and promote a wider use of sandwich panel technology

The central aim of the EASIE (Ensuring Advancement in Sandwich Construction through Innovation and Exploitation) European Project was to facilitate and promote a wider use of sandwich panel technology across the EU Construction industry by removing existing technical, codification and standardization barriers.

From its inception the project has initiated a dialogue between the research team and end-users and has developed and implemented a research communication framework and action plan aimed at bringing together the key results areas, at promoting the outcomes of the work and at improving the end use and market uptake of the research results.

The reasons for the well documented failure of getting research findings into practice are many and include the lack of appropriate information at the point of use, the lack of links and collaboration between the research and user communities, institutional barriers, the use of a format not tailored to the target audience or a widespread resistance to change.

The researchers involved in the EASIE project were well aware of the fact that in order to promote the uptake of their research findings it was incumbent on them to learn how to better communicate with end-users, how to simplify their findings and render them more easily accessible, and how to demonstrate their application and usefulness.

The purpose of this booklet is to present the research findings in a simplified, easily accessible way and to demonstrate their application to users industry and commerce and in particular to SMEs.

Contents

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Structural behaviour

Resistance of panels with openings with reinforcement

Calculation models for large openings

Types of large openings

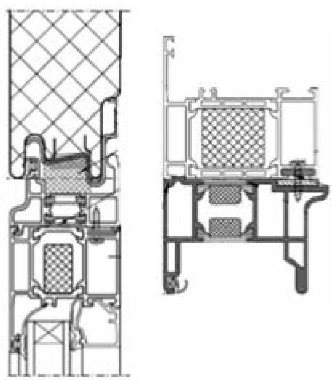
At the moment, there are different types of panel systems for large openings on the market. For windows, one can differentiate between three different categories:

- Ribbon windows with adapter profiles
- Ribbon windows with punctual fixing
- Windows with bonded frames

The load transfer of each of these systems is very different so the calculations model has to be adapted to each type. All the models are based on the existing beam model of Böttcher (2005) which is described in chapter 2.2.2 (Deliverable 1.2).

Ribbon windows with adapter profiles

Based on the beam model of Böttcher (2005) a possibility presents itself: to calculate the load bearing and deflection behavior of sandwich panel systems with ribbon windows and adapter profiles within the joint. The ribbon window itself is not able to transfer the load to the substructure, so the whole load has to be transferred to the adjacent panels. In the figure an example of an adapter profile with and without the sandwich structure is shown.



Beam (1) represents the complete adjacent sandwich panel in longitudinal direction with the related torsional rigidity I_T and the bending stiffness EI_L. The cross-beams (2) represent the behavior in cross direction (EI_Q, G_Q). They have a distance of l_Q. The vertical elements (3) represent the stiffness of the joint kF and the horizontal beam (4) represents the adapter profile with its bending stiffness $EI_{Adapter}$.

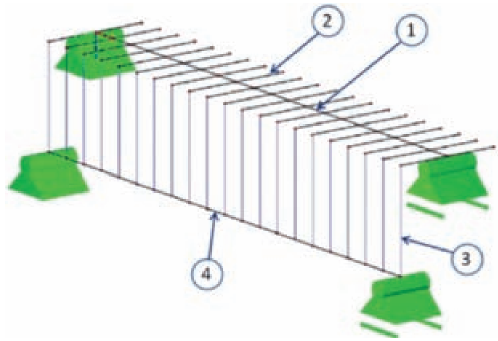


Figure 1: beam model

An assumption for this model is the fact that the adapter profiles are supported by the substructure. The adapter profile is loaded by half of the area load of the window. Depending on the stiffness of adapter profile, joint and sandwich panel the loads will be divided on the adapter profile and the adjacent sandwich panel. The panel is loaded eccentrically which leads to additional stresses in the face and the core material. These stresses have to be added to the stresses caused by the bending moment.

The beam model brings the following results for the particular beams:

Longitudinal beam:	$M_{y,L}$, M_T, $Q_{z,L}$
Cross-beam:	$M_{y,Q}$ and Q_z
Joint elements:	N
Adapter profile:	M_y and Q_z

After the determination of the stress resultants and deflections using the beam model the structural analyses for the different failure modes can be implemented.

The following failure modes are possible:

1 • Wrinkling of the face in the adjacent panel

2 • Shear failure of the core in the adjacent panel

3 • Joint failure

4 • Failure of the adapter profile – This case will not be investigated here as the manufacturer of the adapter profile is usually responsible for the load bearing capacity of the profiles.

1 • Wrinkling of the face:

The normal stress in the adjacent panel can be determined by addition of the normal stress due to bending and the normal stress caused by the eccentric load.

The following two ratios of normal stress in the face exist:

$$\sigma_1 = \frac{M_y}{I_{y,L}} \cdot \left(-\frac{e_c}{2}\right)$$

Existing normal stress due to bending (Independent from the window) **(1)**

$$\sigma_2 = k_\sigma \cdot M_{y,L} \cdot \frac{-e_c}{2 \cdot I_{y,L}}$$ Normal stress due to eccentric loading (2)

The complete stress results in: $$\sigma = (M_y + k_\sigma \cdot M_{y,L}) \cdot \frac{-e_c}{2 \cdot I_{y,L}}$$ (3)

The factor m can be taken from diagrams (See Deliverable 1.2, parametric study, figure 2.8).

The confirmation is then:

$$\gamma_F \cdot (M_y + k_\sigma \cdot M_{y,L}) \cdot \frac{-e_c}{2 \cdot I_{y,L}} \leq \frac{f_{Fck}}{\gamma_M}$$ (4)

2 • Shear failure of the core:

Also in the core the stresses caused by the centric shear force have to be superimposed in the core the stresses from the eccentric loading. For the eccentric load an effective width of the panel of 25 cm (panel width 100 to 120 cm) can be taken into account for conservative results.

The following two ratios of shear stress in the core exist:

Shear stress due to the existing shear force in the panel: $\tau_1 = \frac{Q}{A_L}$ (5)

Shear stress due to the eccentric load: $\tau_2 = \frac{Q_{z,L}}{25\ cm \cdot e_c}$ (6)

The confirmation according to the technical approval is: $\gamma_F \cdot \left(\frac{Q}{A_L} + \frac{Q_{z,L}}{25\ cm \cdot e_c}\right) \leq \frac{f_{cv}}{\gamma_M}$ (7)

3 • Failure of the joint:

For the load transfer from the adapter profile to the adjacent panel the load bearing capacity of the joint has to be proved as well.

The beam model provides the maximum load in the joint as normal force N in the joint elements. The load bearing capacity of the joint Fj has to be determined by tests (See Deliverable 1.2, Chapter 2.2.4).

The result from the beam model is: $F_{joint} = \frac{N}{l_Q}$ (8)

The equation of approval is: $\gamma_F \cdot \frac{N}{l_Q} \leq \frac{F_j}{\gamma_M}$ (9)

Ribbon windows with punctual fixing

In line with the model described above, calculations can also be made for sandwich facades with punctual fixed ribbon windows.
As the windows edges are unsupported the whole load has to be transferred to adjacent panels.

Figure 2: Test setup for a ribbon window with punctual fixing

The calculation and the analyses are the same as described before. Just the load is not applied on an adapter profile but punctual on the crossbeams as described earlier except that the load.

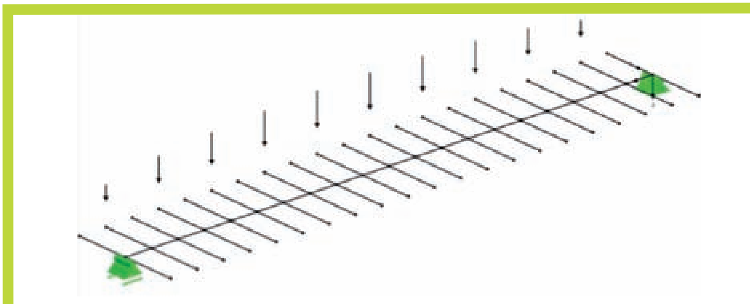


Figure 3: Beam model for the calculation of a sandwich panel in neighborhood of a punctual fixed ribbon window

Additional to the calculation of the panel, the punctual fixing has to be tested. The load bearing capacity of this detail is very dependent on the kind of fixing, so the maximum load should be derived from tests.

Windows with bonded frames

Sandwich facades with bonded window frames have a load bearing behavior which is somewhat different as in this case the whole panel is not replaced by a window (see figure 4). Parts of the panel still participate in the load transfer.

Figure 4: Windows with bonded frames in a sandwich facade

Tests carried out within EASIE have shown that the frames clearly improve the load bearing capacity of the panels. The tests have also shown that the frames do not carry parts of the load by themselves but stabilise the faces in the high stressed regions around the opening. Therefore it is necessary that the frame stabilises the face in a region of at least 5 cm around the opening.

For openings without frames the following basic rules for a centric small opening - derived from the European Recommendations for sandwich panels - are given as the following four equations: 1 to 4:

$$\left.\begin{aligned} \sigma_{Fcd} &= \frac{M_{d.\max}}{e_C\, B\, t_{Fd}} \le k_2 \frac{f_{Fck}}{\gamma_M} \\ \sigma_{Fcd} &= \frac{M_{od}(x)}{e_C\, B\, t_{Fd}} \le k_2 k_F \frac{f_{Fck}}{\gamma_M} \end{aligned}\right\} \quad (10)$$

where

$$k_F = \begin{cases} (1-\beta)^2 \text{ if } 0 \le \beta \le 0.4 \\ 0.6(1-\beta) \text{ if } 0.4 < \beta \le 0.8 \end{cases} \quad (11)$$

$$k_2 = (6.10 f_{Ct} + 0.39) \leq 1.0 \quad (12)$$

$$\beta = b/B \quad (13)$$

The load bearing capacity of single panels with small openings can be derived from these equations. The factor k_F has to be adapted for the bonded frames to the factor $k_{F,frame}$:

$$k_{F,i} = \begin{cases} (1-\beta_i)^2 & if \quad 0 \leq \beta_i \leq 0{,}4 \\ 0{,}6 \cdot (1-\beta_i) & if \; 0{,}4 < \beta_i \leq 0{,}8 \end{cases} \quad (14)$$

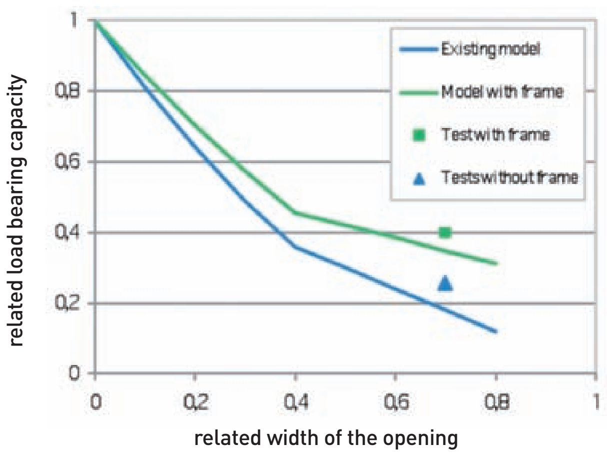


Figure 5: Load bearing capacity of panels with reinforced openings

Please note that the model proposed above is based on a limited number of tests and will therefore have to be further verified with additional experiments.

For openings through longitudinal joints as shown in figure 6 below the load bearing capacity is always the sum of the residual load bearing capacities of the outer panels. In case of a single span panel the inner panels do not contribute to the load transfer.

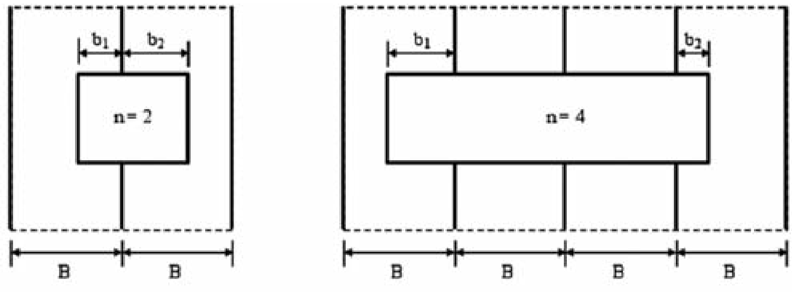


Figure 6: Geometries of large openings

The calculated load bearing capacity is very depending on the calculation model. If the panels are supported laterally, they are able to carry much more load than laterally unsupported panels. In figure 7 the related load bearing capacity for a system of two panels with an opening (width of the opening 1 m, according to figure 6, left side) with different eccentricities is compared for lateral supported and lateral not supported panels.

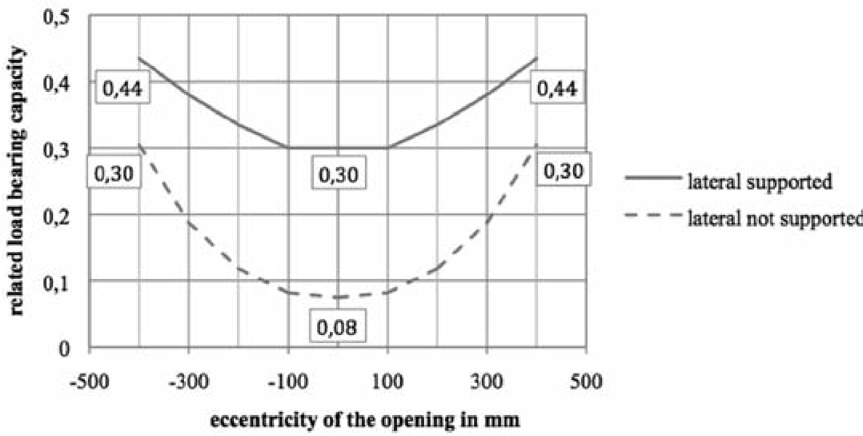


Figure 7: Load bearing capacity for a system of two panels with one opening (Width of the opening 1 m)

Due to the neighboring panels and the bonding between the window frame and the panels a lateral support can be assumed. In this case the following equation can be used:

$$\sigma_{Fcd} = \frac{M_{od}(x)}{e_c \cdot B \cdot t_{Fd}} \leq k_2 \cdot \frac{k_{F1}+k_{F2}}{n} \cdot \frac{\sigma_w}{\gamma_M} \quad (15)$$

with

$$k_{F,i} = \begin{cases} (1-\beta_i)^2 & if \quad 0 \leq \beta_i \leq 0{,}4 \\ 0{,}6 \cdot (1-\beta_i) & if \; 0{,}4 < \beta_i \leq 0{,}8 \end{cases} \quad (16)$$

The equations 15 and 16 directly result from equation 10 and 11 as sum of the load bearing capacities of the outer panels.

The result for the system tested within EASIE (See Deliverable 1.2, Chapter 2.4.2, Test 1 three panels with an opening with a width of 1,9m) is shown in figure 8. For this test a good correlation between the test result and the calculation proposal can be stated.

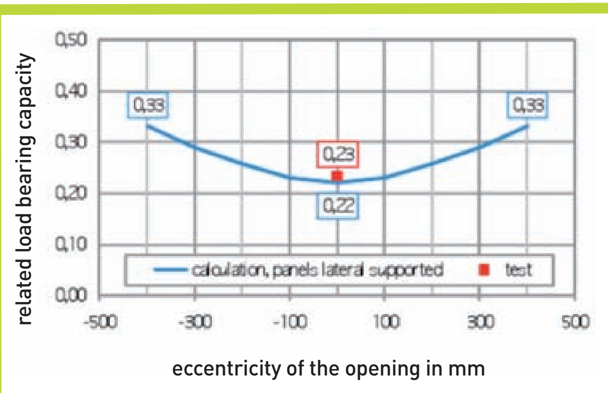


Figure 8: All the models above are based on very few tests, so further investigations are necessary to verify these proposals!

Further information

Further information on the structural behavior of sandwich panels with openings can be found in the following report, which can be downloaded at www.easie.eu:

Deliverable D1.2:
Calculation Model determining mechanical strength of sandwich panels with openings with and without additional internal frame structure

Furthermore different papers on this topic were published:

- Warmuth, F., Lange, J.: *"Openings in Sandwich Elements"*, CIB World Congress 2010.
  Proceedings (www.cib2010.org/post/files/papers/1013.pdf).
- Rädel, F., Lange, J.: *"Tragfähigkeit von Sandwichelementen mit profilierten Deckschichten und Öffnungen)"*, Stahlbau, Vol. 80, No. 9, 2011 (in German).
- Rädel, F., Lange, J.: *"Eccentrically loaded Sandwich Elements"*, EUROSTEEL 2011, Budapest, September 2011.

References

Böttcher, M. 2005, Berechnungsverfahren für Wand-Sandwichelemente mit Öffnungen.

IFBS-Fachinformation 5.09 Statik, IFBS e.V, Düsseldorf (in German)

Courage, W. & Toma T. 1994, Structural detailing of openings in sandwich panels. TNO report 94-CON-R0729-01

2

Thermal behaviour

Principles of good practice

Fabrication of sandwich panels

Panels with core material of closed cell structure

The geometry of the joint can greatly contribute to air and water penetration. The key and slot joints in panelscan have a positive influence on the tightness. In this context it is very important that the abutting ends and surfaces of the panels fit into one another very well. For a good insulation it is also important that the metal faces have as little penetration into the core as possible like it is shown in the right picture of figure 1.1. A bad solution is to have the metal face bent into the core as it is done in the panel to the left in figure 1.1. The problem is of particular importance for thin panels (thicknesses up to 80 mm) where there are cases where the metal faces almost touch each other in the joint. Joints always form a line of higher thermal conduction as in the panel area and the penetration of metal worsens this [IFBS 4.03].

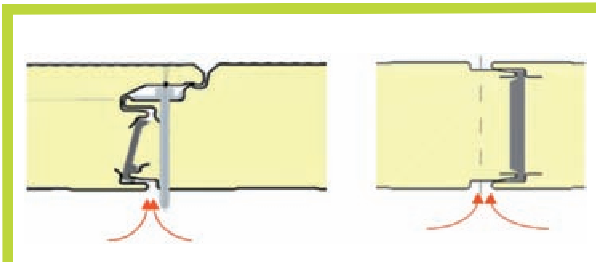


Figure 1.1: Experimental set-up

The next important element is the sealing tape. Current state of the art is to use sealing tapes in every longitudinal joint of the panels. Different kinds of sealing tapes exist on the market [IFBS

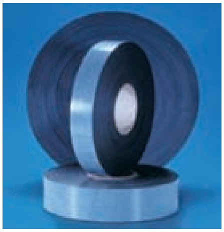
4.02]. The most important difference is in the cell structure with open cells, partly open cells and closed cells all used in modern sandwich panels.

These different structures lead to very different characteristics regarding the air permeability. Closed cell structures are practical completely airtight as soon as they have contact to the joint, whereas open structures need some compression. The required level of compression is depending on the cellular material. According to [Galileo], the following table gives some guide values:

Cellular Material	Minimal compression for air tightness
PUR-foam, open cells	60 – 80 %
PUR-foam, open cells, impregnated by acrylate	50 – 60 %
PVC-foam, partly open cells	30%
PE-foam, partly open cells	15 %
PE-foam, closed cells	-

In addition good results have been obtained with rope seals or rubber piping made of EPDM (ethylene propylene diene Monomer).

Impregnated open celled PUR-foam [www.iso-chemie.com]



Closed celled PE-foam [www.iso-chemie.com]

Figure 1.2: Examples of sealing tapes

According to that information it is essential for the tightness that the geometry of the joint allows the required compression of the sealing joint.

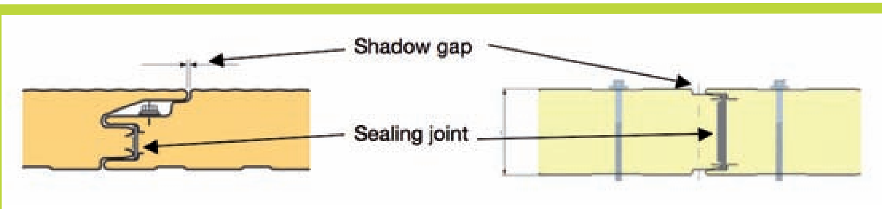


Figure 1.3: Examples of longitudinal joints

If the shadow gap is closed for example before the sealing joint is compressed, it will not be possible to get an air tight construction. In addition the effectiveness of the contact pressure plays an important role. If the necessary compression can only be reached by high pressure, the correct mounting equipment has to be used.

Panels with core material of open cell structure

For panels with core material of open cell structure such as mineral wool a different sealant solution is necessary. By these panels a sealant stripe of tight material with big flexibility shall be placed in the longitudinal joint between the metal sheets. Here it is very important to seal the joint between the sheets; otherwise an air stream through the open cell structure of the core is possible. The joint profile geometry shall be designed for this sealant stripe. Two examples are shown in figure 1.4. The sealant shall be placed on the warm side. In special cases, e.g. walls with high wind pressure, sealants in both faces as shown in figure 1.4 (on the left) can be useful.

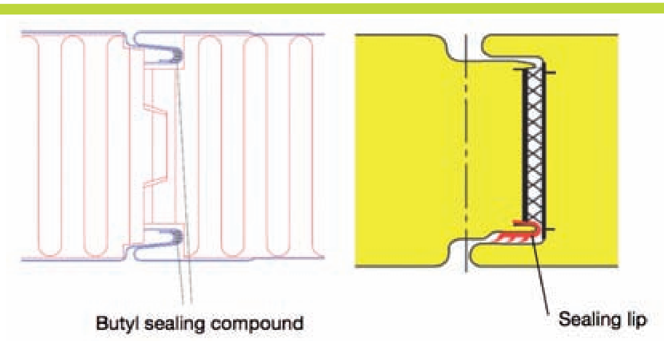


Figure 1.4: Examples for a good sealing of mineral wool panels [www.Ruukki.com], [www.fischerprofil.de]

Also for mineral wool panels, the tolerances play an important role. They have to be small enough to assure the sealing.

Installation of sandwich panel constructions

Sandwich panels are usually optimised for fabrication by the panel manufacturer. Due to the fact that the joints are fabricated in an industrial process very small tolerances are possible. So the question of tightness is mostly a question of a correct installation. For example TKS writes in his installation recommendations: "It is not possible to correct the position of subsequent panels by realigning the longitudinal joint. Sealing of the longitudinal joint is achieved by factory-applied sealing strips. Tightness, however, is only ensured when the modular laying dimension is exactly adhered to."

For ensuring the air and water tightness of the panels an exact knowledge of the tolerable width of the shadow gap (see fig. 1.3) is necessary. This is the only possibility for the fitter to check the correctness of the construction and to guarantee a tight building envelope. The tolerances have to be small enough to assure the required compression. Fabricators must give a value for the nominal shadow gap and tets must be performed with a nominal gap of + 1mm.

Joints sealing openings

In addition to the rules for longitudinal joints which are important for joints sealing openings as well there is another point to give attention must be given to a further point. Because of different joint geometries different sealing strips are used. An incorrect installation of the seal will result in a lack of tightness especially in the corners of the openings.

Figure 1.5: Example for an installed window in laboratory with longitudinal and horizontal sealing tapes

Further information

Further information on the thermal behaviour can be found in the following report, which can be downloaded at www.easie.eu:

Deliverable D1.1:
Design guidelines for good panel joints and joints sealing openings focussing on air and water tightness

References

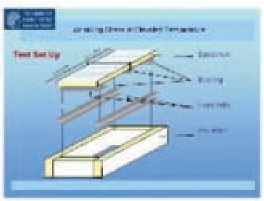
Galileo – Kreatives Bauen mit Sandwich: Basis Info, chapter 4.9, Version 2009-11-D1

IFBS 4.02, Bauphysik – Fugendichtheit im Stahlleichtbau, IFBS e.V., Düsseldorf, 11/2004

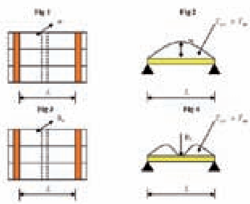
IFBS 4.03, Bauphysik – Wärmebrückenatlas der Metall-Sandwichbauweise, IFBS e.V., Düsseldorf, 03/2010

3

The thermal test methods



Thermal test equipment
Darmstadt university



Thermal test procedure

Test equipment: the supports

System to apply the load

The standard EN 14509 allows to calculate a coefficient k1 applied on the stresses.

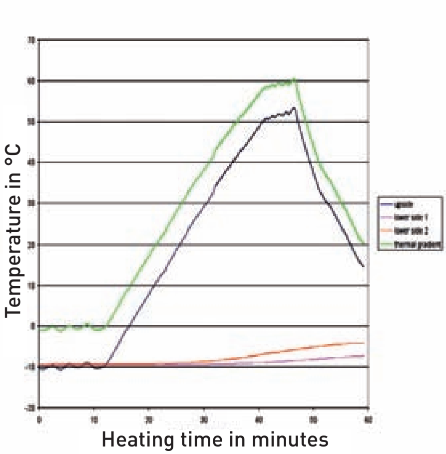
Alternative thermal methods are proposed either to see the influence of the temperature on the bending moments either to compare the real deflection with the theoretical deflection due at the temperature.

Two methods are defined:

Method 1:

It's aim is :

- to calibrate the theory and the real behaviour of the panel (coefficient $\beta_{\Delta T} = w_{test} / w_{theory}$)
- to evaluate the thermal action on the central support of a panel on 3 supports below a thermal gradient alone



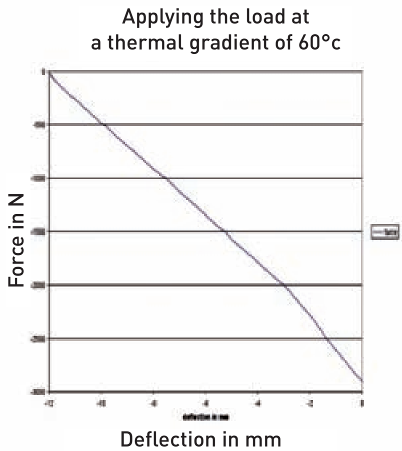


Table of results for a thermal gradient of 50°C

Test No.	Material	thickness	span	DT	f measured	f theoretical	β
1	PUR	100	2,895	59,65	7,70	7,74	0,99
2	PUR	100	3,999	58,38	12,56	13,60	0,92
3	PUR	80	2,895	60,00	9,79	9,91	0,99
4	PUR	80	3,895	56,76	15,74	16,70	0,94
5	MW	90	2,895	59,00	8,63	8,39	1,03
6	MW	90	3,895	55,00	14,51	14,08	1,03
7	MW	120	2,895	59,40	6,16	6,27	0,98
8	MW	120	3,895	55,00	10,86	10,52	1,03

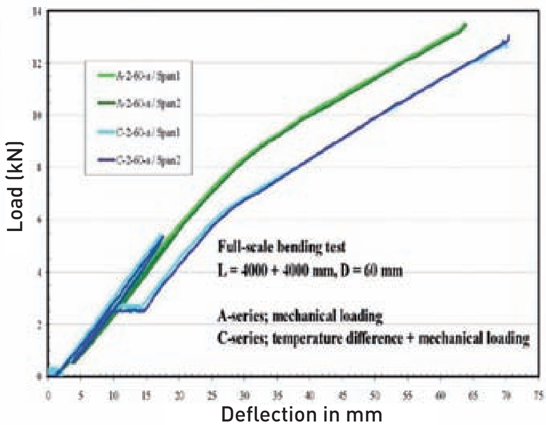
Method 2:

It's aim is :

- to calibrate the design by calculation and design by testing procedure in general when a thermal gradient is applied, find equivalent k_1 factor (see EN 14509 formula A.16).

In this method, a thermal gradient is first applied, followed by an additional loading in the form of a series of linear punctual loads.
Thus the behaviour of the panel below thermal gradient and loading is directly known.
The comparison of the results with and without thermal gradient are possible and the effect of the thermal gradient is taken into account in a real way.
This test is an alternative way at the correction by k1 the wrinkling stress due to the temperature.

Thermal test equipment
Aalto university Finland



Example of test results for a roof panel on 3 supports (In green) without thermal gradient, loading alone ,and in blue below a thermal gradient of 40°C + loading

4

Design by testing package

An information of this work was given to the relevant European codification technical committees.

This work constitutes a background that will be used and discussed in the TC128SC11 WG5 and WG1 to build the final version of the annex about the design by testing in the EN 14509.

The aim of the study was to develop the method and analyse the advantages which design by testing could offer as an alternative to design by calculation, which is developed in the EN 14509.

The main outputs from the study are:

- A summary of the basic principles of design by testing
- Two thermal test methods are proposed: equivalent k1 coefficient by test, and verification of the theoretical and real behaviour below thermal gradient
- 2 Theoretical guidelines with a formula to calculate the strength of the material for flat and for ribbed panel
- 31 Numerical examples including PU and MW panels, cladding and roofing, on 2 and 3 support, in pressure and suction and with and without thermal gradient
- Three Excel sheets which allow for quick and easy hand calculation by hand for the numerical examples
- Parametric study comparing the design by testing results with those obtained following EN 14509. This study allows to see through several load tables the advantages offered by the design by testing method.

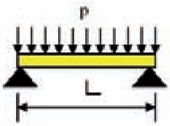
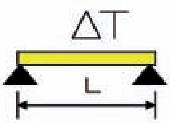
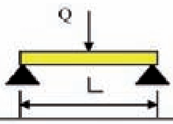
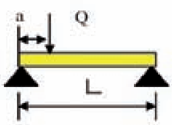
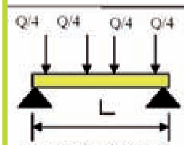
The design by testing guidelines : Deliverable 2.3

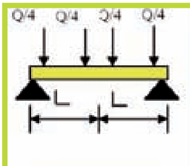
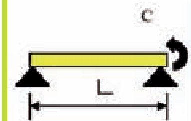
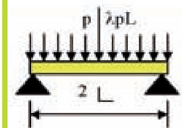
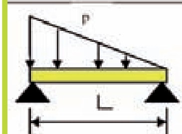
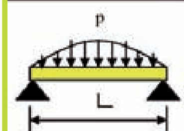
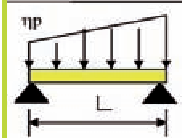
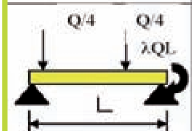
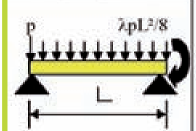
Two guidelines have been developed to justify the formula used for the design by testing and that can be also used for the design by calculation.

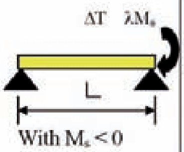
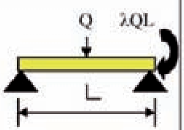
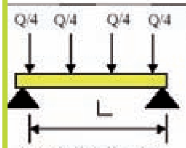
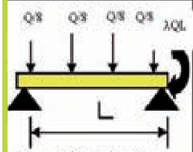
- Guideline No 1 deals with flat panels without ribs (cladding panels)
- Guideline No 2 deals with ribbed panels with ribs on one face (roof panels)

Example of results that can be used both for design by testing and design by calculation (the two first cases are already in the EN 14509 standard (see table E.10.2).

The parametra λ, for the equivalent two span panels, is determined either by calculation (formula in cosh ECCS etc Stamm and Witte) or by testing by measurement of the action on the central support or by forfeiture value.

Loading	Shear end support	factor ξ	Bending moment M_{Fl}	Bending moment M_s	Deflection at mid span
	$\frac{pL}{2}$	$\frac{16}{5}$	$\frac{pL^2}{8}\beta$	$\frac{pL^2}{8}(1-\beta)$	$\frac{5pL^4}{384B_s}\left(1+\frac{16}{5}K\right)(1-\beta)$
	0	$\frac{8}{3}$	$B_{Fl}\frac{\alpha\Delta T}{e}(1-\beta)$	$-B_{Fl}\frac{\alpha\Delta T}{e}(1-\beta)$	$\frac{\alpha\Delta TL^2}{8e}(1-\beta)$
	$\frac{Q}{2}$	4	$\frac{QL}{4}\beta$	$\frac{QL}{4}(1-\beta)$	$\frac{QL^3}{48B_s}(1+4K)(1-\beta)$
	$\frac{Q(L-a)}{L}$ (left) $\frac{Qa}{L}$ (right)	For $0\le a\le L/2$ $\frac{8}{3-4\left(\frac{a}{L}\right)^2}$ For $L/2\le a\le L$ $\frac{8}{3-4\left(\frac{L-a}{L}\right)^2}$	For $x=a$ $\frac{Q(L-a)a}{L}\beta$	For $x=a$ $\frac{Q(L-a)a}{L}(1-\beta)$	For $0\le a\le L/2$ $\frac{QL^2a}{48B_s}\left[3-4\left(\frac{a}{L}\right)^2\right]\left(1+\left\{\frac{8}{3-4\left(\frac{a}{L}\right)^2}\right\}K\right)(1-\beta)$ For $L/2\le a\le L$ $\frac{QL^2(L-a)}{48B_s}\left[3-4\left(\frac{L-a}{L}\right)^2\right]\left(1+\left\{\frac{8}{3-4\left(\frac{L+a}{L}\right)^2}\right\}K\right)(1-\beta)$
 Load distribution 0.1L, 0.3L,0.2L,0.3L,0.1L	$\frac{Q}{2}$	$\frac{100}{31}$	$\frac{QL}{8}\beta$	$\frac{QL}{8}(1-\beta)$	$\frac{31QL^3}{2400B_s}\left(1+\frac{100}{31}K\right)(1-\beta)$

 Load distribution L/8, 21L/40, 7L/20, 7L/20, 21L/40, L/8	$\frac{Q}{2}$	$\frac{99200}{131099}$	$\frac{31QL}{160}\beta$	$\frac{31QL}{160}(1-\beta)$	$\frac{131099QL^3}{1536000B_s}\left(1+\frac{99200}{131099}K\right)(1-\beta)$
	$\frac{C}{L}$	0	$C\beta$	$C(1-\beta)$	$\frac{CL^2}{16B_s}(1-\beta)$
	$pL+\frac{\lambda pL}{2}$	$\frac{4(1+\lambda)}{(5+4\lambda)}$	$\frac{pL^2}{2}(1+\lambda)\beta$	$\frac{pL^2}{2}(1+\lambda)(1-\beta)$	$\frac{pL^4}{24B_s}(1+\xi K)(5+4\lambda)(1-\beta)$
	$\frac{pL}{3}$ (left) $\frac{pL}{6}$ (right)	$\frac{16}{5}$	$x=L\left(1-\frac{1}{\sqrt{3}}\right)$ $\frac{pL^2}{9\sqrt{3}}\beta$	$x=L\left(1-\frac{1}{\sqrt{3}}\right)$ $\frac{pL^2}{9\sqrt{3}}(1-\beta)$	$\frac{5pL^4}{768B_s}\left(1+\frac{16}{5}K\right)(1-\beta)$
	$\frac{pL}{3}$	$\frac{200}{61}$	$\frac{5pL^2}{48}\beta$	$\frac{5pL^2}{48}(1-\beta)$	$\frac{61pL^4}{5760B_s}\left(1+\frac{200}{61}K\right)(1-\beta)$
	$\frac{pL}{6}(1+2\eta)$ (left) $\frac{pL}{6}(2+\eta)$ (right)	$\frac{16}{5}$	$\frac{p}{2L}\left(\frac{x^3}{3}(-1+\eta) - L\eta x^2 + \frac{L^2x}{3}(1+2\eta)\right)\beta$ $x=\frac{\eta-\sqrt{\frac{1}{3}(\eta^2+\eta+1)}}{\eta-1}L$	$\frac{p}{2L}\left(\frac{x^3}{3}(-1+\eta) - L\eta x^2 + \frac{L^2x}{3}(1+2\eta)\right)(1-\beta)$ $x=\frac{\eta-\sqrt{\frac{1}{3}(\eta^2+\eta+1)}}{\eta-1}L$	$\frac{5pL^4(1+\eta)}{768B_s}\left(1+\frac{16}{5}K\right)(1-\beta)$
 Load distribution L/8, 21L/40, 7L/20	$\left(\frac{49}{160}-\lambda\right)Q$ (left) $\left(\frac{31}{160}+\lambda\right)Q$ (right)	$\frac{1}{\frac{1049}{3200}-\frac{60\lambda}{19}}$	$x=26L/40$ $\left(\frac{217}{3200}-\frac{13\lambda}{20}\right)QL\beta$ $x=L/8$ $\left(\frac{49}{1280}-\frac{\lambda}{8}\right)QL\beta$	$x=26L/40$ $\left(\frac{217}{3200}-\frac{13\lambda}{20}\right)QL(1-\beta)$ $x=L/8$ $\left(\frac{49}{1280}-\frac{\lambda}{8}\right)QL(1-\beta)$	$\frac{QL^3}{B_s}\left(\frac{19931}{3072000}-\frac{\lambda}{16}\right)\times$ $\left(1+\frac{1}{\left(\frac{1049}{3200}-\frac{60\lambda}{19}\right)}K\right)(1-\beta)$
	$\frac{pL}{2}-\frac{\lambda pL}{8}$ (left) $\frac{pL}{2}+\frac{\lambda pL}{8}$ (right)	$\frac{16}{5-3\lambda}$	$\left(\frac{Lx}{2}-\frac{x^2}{2}-\frac{\lambda L}{8}x\right)p\beta$	$\left(\frac{Lx}{2}-\frac{x^2}{2}-\frac{\lambda L}{8}x\right)p(1-\beta)$	$\frac{5pL^4}{384B_s}(5-3\lambda)\left(1+\frac{16}{5-3\lambda}K\right)(1-\beta)$

 With $M_s < 0$	$\frac{\lambda M_s}{L}$ (left) $-\frac{\lambda M_s}{L}$ (right)	$\frac{16}{3(2+\lambda)}$	$\beta\left(\frac{\lambda M_s}{L}\right)x+$ $\left(\frac{\alpha\Delta T}{e}\right)(1-\beta)B_{F1}$	$(1-\beta)\left(\frac{\lambda M_s}{L}\right)x-$ $\left(\frac{\alpha\Delta T}{e}\right)(1-\beta)B_{F1}$	$\frac{\alpha\Delta T L^2}{8e}(1-\beta)+\frac{\lambda M_s L^2}{16B_s}(1-\beta)$
	$\frac{Q}{2}-\lambda Q$ (left) $\frac{Q}{2}+\lambda Q$ (right)	$\frac{4}{1-3\lambda}$	$0 \le x \le L/2$ $\beta\left[\frac{1}{2}-\lambda\right]Qx$ $L/2 \le x \le L$ $\beta\left[-\frac{x}{2}-\lambda x+\frac{1}{2}\right]Q$	$0 \le x \le L/2$ $(1-\beta)\left[\frac{1}{2}-\lambda\right]Qx$ $L/2 \le x \le L$ $(1-\beta)\left[-\frac{x}{2}-\lambda x+\frac{1}{2}\right]Q$	$\frac{QL^2}{48B_s}(1-3\lambda)\left(1+\frac{4}{1-3\lambda}K\right)(1-\beta)$
 Load distribution	$\frac{Q}{2}$	$\frac{128}{41}$	$\frac{QL}{8}\beta$	$\frac{QL}{8}(1-\beta)$	$\frac{41QL^3}{3072B_s}\left(1+\frac{128}{41}K\right)(1-\beta)$
0.125L, 0.25L,0.25L,0.25L,0.125L					
 Load distribution 0.125L, 0.25L,0.25L,0.25L,0.125L	$\frac{Q}{4}-\lambda Q$	$\frac{1}{\frac{41}{128}-3\lambda}$	$x = L/2$ $\left[\frac{QL}{16}-\lambda\frac{QL}{2}\right]\beta$	$x = L/2$ $\left[\frac{QL}{16}-\lambda\frac{QL}{2}\right](1-\beta)$	$\frac{QL^3}{B_s}\left(\frac{41}{6144}-\frac{\lambda}{16}\right)\times$ $\left(1+\left[\frac{1}{\left(\frac{41}{128}-3\lambda\right)}\right]K\right)(1-\beta)$

With:

$$\beta=\frac{B_{F1}}{B_{F1}+\frac{B_s}{1+\xi K}} \quad K=\frac{3B_s}{G_c A_c L^2} \quad (1-\beta)=\frac{B_s}{\left[(1+K\xi)B_{F1}+B_s\right]}$$

The examples: Deliverable 2.4

31 examples were carried out covering:

- cladding panels of Panelco, Thussenkrupp with PU and mineral wool core on 2 and 3 supports with positive and negative loading
- Roofing panel of AMC Polska with PU core on 2 and 3 supports with positive and negative loading with and without thermal gradient.

For each example are defined: the panel tested, the tests which have been performed and their results and the interpretation of the tests results to determine the bending and shear rigidity (Bs and GcAc), the strength capacities. Moment in span and on central support, shear on end and central support, reaction to support capacity on end and central support in ULS (Elastic and elaso-plastic approach) and SLS and the load span tables.

The excel sheets: Deliverable 2.5

Three type of Excel sheets have been developed and are freely accessible on the EASIE website (www.easie.eu):

1 • To determine the bending and shear rigidities

Elastic behaviour

Flat panel on 3 supports (K method)
© 2011, SNPPA

	Units	For the spans tested		
	m	3,06	4,06	6,06
Q_d	daN	761	400	500
w_d	m	0,002678	0,002127	0,00529
t_1	mm	0,6	0,6	0,6
$t_{1,obs}$	mm	0,568	0,568	0,568
t_2	mm	0,6	0,6	0,6
$t_{2,obs}$	mm	0,561	0,561	0,561
D	mm	140	140	140
D_{obs}	mm	140,14666	140,28	139,96
G_c	MPa	5,73	5,73	5,73
$G_{c,obs}$	MPa	8,74	8,74	8,74
Correction factor B_{sk}		1,06070488	1,05868938	1,06353602
Correction factor $G_c A_{ck}$		0,65492033	0,65429781	0,65579378

Span considered (m)		3,06	3,06	4,06
		4,06	6,06	6,06
		Rigidities without corrections		
B_{sk}	daN.m²	134868,05	129942,243	128314,569
$G_c A_{ck}$	daN	72509,3512	73171,0275	73902,8349
		Rigidities with corrections		
B_{sk}	daN.m²	142919,285	138014,313	136156,219
$G_c A_{ck}$	daN	47465,2791	47953,149	48409,7412

2 • To determine the strength capacities

Elastic behaviour (ULS)

	Units	For the spans tested			Lshear test
	m	3	4	4	3
Q_{cs}	daN	1404	1250	1250	L1 (m)
R_{cs}	daN	824	750	750	0,4
$Q_{cv(shear\ test)}$	daN	974,4			
$k_{e,central}$		0,1	0,11	0,12	
$k_{e,end}$		0,2	0,21	0,22	
f_{y1}	Mpa	300	300	300	
$f_{y1,obs}$	MPa	402	402	402	
f_{y2}	Mpa	320	320	320	
$f_{y2,obs}$	MPa	395	395	395	
t_1	mm	0,5	0,5	0,5	
$t_{1,obs}$	mm	0,427	0,427	0,427	
t_2	mm	0,5	0,5	0,5	
$t_{2,obs}$	mm	0,435	0,435	0,435	
D	mm	60	60	60	
D_{obs}	mm	61,76	61,36	61,36	
f_{cv}	MPa	0,13	0,13	0,13	
$f_{cv,obs}$	MPa	0,1366	0,1366	0,1366	
f_{cc}	MPa	0,12	0,12	0,12	
$f_{cc,obs}$	MPa	0,119	0,119	0,119	
B_{obs}	mm	1000	1000	1000	
L_s	mm	60	60	60	
α M3A		0,5	0,5	0,5	
β M3A		1	1	1	
α M3T		0,5	0,5	0,5	
β M3T		1	1	1	
γ_m bending		1,1	1,1	1,1	
γ_m shear		1,25	1,25	1,25	
k (bending)		0,85	0,85	0,85	
k (shear)		0,85	0,85	0,85	
k(shear test)		0,829	0,829	0,829	
λ_{cs}		0,043447293	0,05	0,05	

3 • To determine the load tables

	Units	Elastic behaviour Qcs		
		For the spans tested		
	m	3	4	4
$M_{U3A,Rd\Delta T}$	daN.m	149,87	139,4	139,4
$M_{U3T,Rd\Delta T}$	daN.m	186,64	321,5	321,5
$V_{U3T,Rd\Delta T}$	daN	1297	1297	1297
$V_{U3A,Rd\Delta T}$	daN	422,6052	460,4	460,4
$P_{U3T,Rd}$	daN	1449,26	1297	1297
$P_{U3A,Rd}$	daN	944,65	920,8	920,8

$\lambda_{Q,csi,test}$	0,02285219	0,00457	0,00457
$\lambda_{\Delta T,c,test}$	0,179218	0,318578	0,318578

	Combination factors			
	for G	for Q	for ΔT	Case
ULS	1,35	1,5	0,9	Strength
	1,35	0,9	1,5	Strength
	1,35	1,5	0	Strength

Span studied (m)
3
3,25
3,3
3,4
3,45
3,5
3,6
3,75
4
4,1
4,2
4,25
4,3
4,4
4,5
4,6
4
6,25
6,5
6,75
7

Bending rigidities		Units
$B_{s\Delta T(fixed)}$	58122,85	daN.m²
$B_{F1(fixed)}$	1478	daN.m²
$G_c A_{c\Delta T(fixed)}$	31267	daN
φ	0	

$G_c A_{c\Delta T}$	31267	daN
$(1+\varphi)$	1	

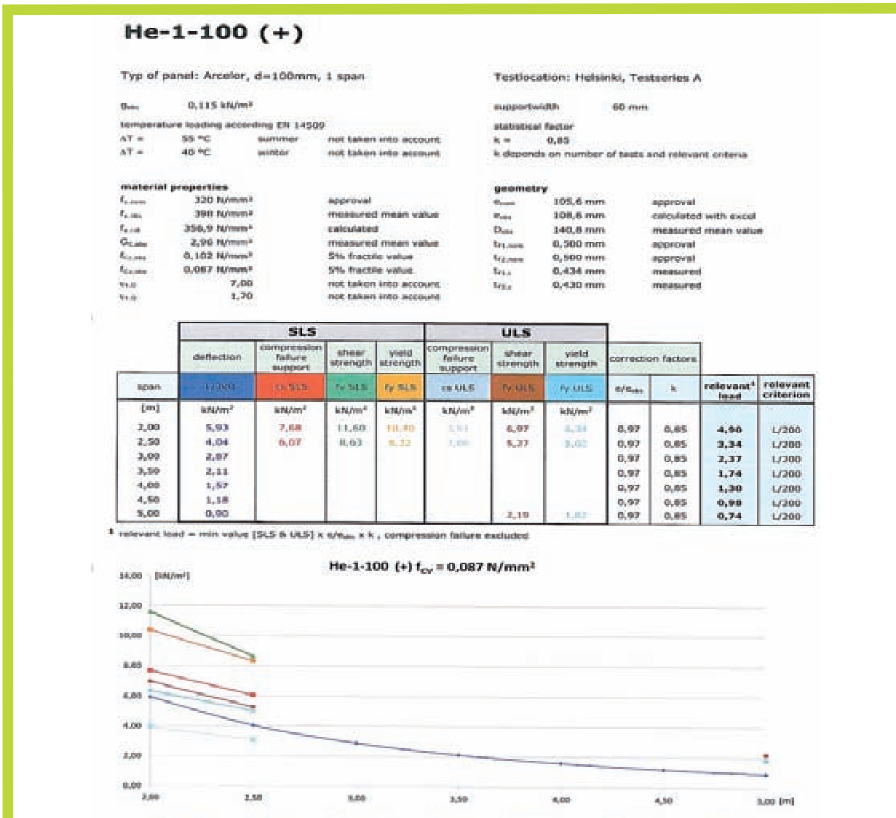
Loading fixed		Units
Self weight	12,63	daN/m²
Thermal gradient winter	40	°C
Width of the panel	1000	mm
Deflection criteria L/	200	
Thermal gradient summer	0	°C
Alpha	1,20E-05	(/°C)
e (thickness panel)	0,1	m

The parametric study (Deliverable 2.2)

Extensive parametric studies were carried out to compare the results of the design by testing method with the design by calculation defined in the EN 14509.

The design by testing allows to have some benefit by comparison with the design by calculation approach in terms of load/span tables.

This is due at the test done in the end use condition and by the use of the rest moment when it's significant.



He-1-100 (+)

Typ of panel: Arcelor, d=100mm, 1 span

Testlocation: Helsinki, Testseries A

g_{obs} 0,115 kN/m²

temperature loading according EN 14509

ΔT = 55 °C summer not taken into account

ΔT = 40 °C winter not taken into account

supportwidth 60 mm

statistical factor

k = 0,85

k depends on number of tests and relevant criteria

material properties

$f_{y,nom}$	320 N/mm²	approval
$f_{y,obs}$	390 N/mm²	measured mean value
$f_{y,cal}$	356,9 N/mm²	calculated
$G_{C,obs}$	2,96 N/mm²	measured mean value
$f_{Cc,obs}$	0,102 N/mm²	5% fractile value
$f_{Cv,obs}$	0,087 N/mm²	5% fractile value
$\gamma_{1,0}$	7,00	not taken into account
$\gamma_{1,0}$	1,70	not taken into account

geometry

e_{nom}	105,6 mm	approval
e_{obs}	108,6 mm	calculated with excel
D_{obs}	140,8 mm	measured mean value
$t_{F1,nom}$	0,500 mm	approval
$t_{F2,nom}$	0,500 mm	approval
$t_{F1,c}$	0,434 mm	measured
$t_{F2,c}$	0,430 mm	measured

	SLS				ULS			correction factors			
	deflection	compression failure support	shear strength	yield strength	compression failure support	shear strength	yield strength				
span	L/200	cs SLS	fv SLS	fy SLS	cs ULS	fv ULS	fy ULS	e/e_{obs}	k	relevant[1] load	relevant criterion
[m]	kN/m²	kN/m²	kN/m²	kN/m²	kN/m²	kN/m²	kN/m²				
2,00	5,93	7,68	11,60	11,40	[illegible]	6,97	4,34	0,97	0,85	4,90	L/200
2,50	4,04	6,07	8,03	8,22	[illegible]	5,27	3,02	0,97	0,85	3,34	L/200
3,00	2,87							0,97	0,85	2,37	L/200
3,50	2,11							0,97	0,85	1,74	L/200
4,00	1,57							0,97	0,85	1,30	L/200
4,50	1,18							0,97	0,85	0,98	L/200
5,00	0,90					2,19	1,82	0,97	0,85	0,74	L/200

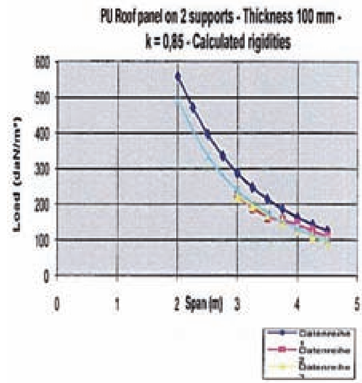
[1] relevant load = min value [SLS & ULS] x e/e_{obs} x k , compression failure excluded

He-1-100 (+) f_{Cv} = 0,087 N/mm²

Calculation From Is Mainz

	Panel 1 on 2 supp-thickness 100m	Positive loading			
WP2 doc 55	rev 5	(k=0,85)			
Span (m)	Load table Design by tes	load table	load table	Load table EN 14509	
2	557			490	L/200
2,25	470				
2,5	394			334	L/200
2,75	334				
3	285	220	220	237	L/200
3,25	246	189	195		
3,5	212	163	170	174	L/200
3,75	185	152	150		
4	161	141	130	130	L/200
4,25	141	123	110		
4,5	124	108	95	98	L/200

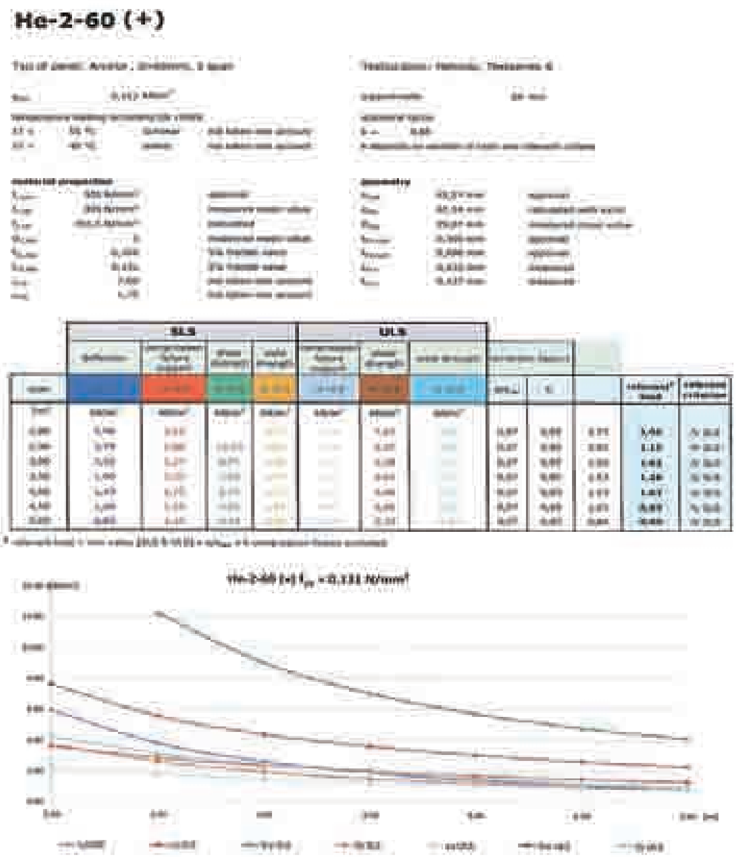
Design by testing Calculation By D I



In blue light design by calculation (Is Mainz) and dark blues design by testing (DI)

	Panel on 3 supp - thickness 60m	Positive loading			
WP2 doc 63		(k=0,85)	In elastic plastic		
Span (m)	Load table Design by tes	load table	load table	Load table EN 14509	
2	356			306	fy SLS
2,25	320				
2,5	283	236		215	fy SLS
2,75	256	181			
3	227	144	250	161	fy SLS
3,25	194	113	220		
3,5	167	91	200	126	fy SLS
3,75	138	83	180		
4	128	75	160	101	fy SLS
4,25	119	63	150		
4,5	105	53	130	83	fy SLS

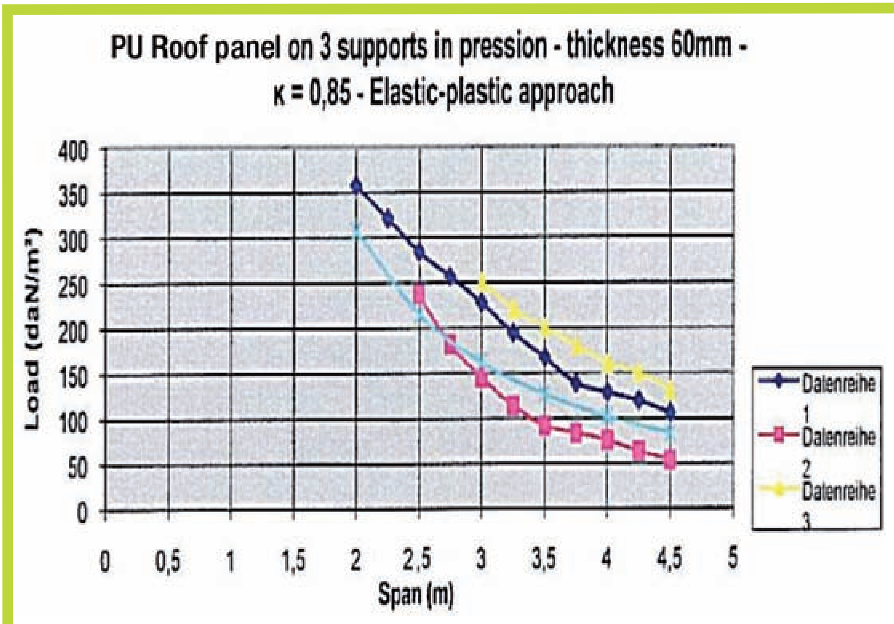
Design by testing Calculation By D I


He-2-60 (+)

SLS

ULS

Calculation From Is Mainz



In blue light design by calculation (Is Mainz) and dark blues design by testing (DI)

Roof PU panel from AMC Polska, PU and MW Cladding panels from Thyssen, and Panelco have been studied on 2 and 3 supports, in pression and suction, with and without thermal gradient.

SNPPA performed the calculations while IsMainz have verified and compared them with EN14509.

Some key illustrative results are given in the above figure.

A draft annex for the TC128 SC11

A draft annex on the design by testing is being prepared in collaboration with the European Committee for Standardization (CEN) TC128 SC11 based on the EASIE results.

This annex will define the general procedure of the design by testing and the principal formula that must be used. The principles are given below:

The Principe of the design by testing is to verify that: $S_d \leq R_d$

All the limit states require to verify the following set of equations:

At ULS:

$$S_{U,Sd} = \gamma_G G + \gamma_{Q1} Q_{k1} + \sum_{i>1} \psi_{0i} \gamma_{Qi} Q_{ki} \leq S_{U,Rd} = k \times R_{ad,S} \times \frac{f_{test(Q_c)}}{\gamma_M}$$

At SLS:

$$S_{E,Sd} = \sum_{j>1} G_{kj} + Q_{k1} + \sum_{i>1} \psi_{0i} Q_{ki} \leq S_{E,Rd} = k \times R_{ad,S} \times \frac{f_{test(Q_{ei/dp})}}{\gamma_M}$$

The deflection criteria:

$$w = \frac{f_{(Q)}}{\beta(B_s; G_c A_c)} \leq \frac{L}{X} \qquad S_{E,Sd} = \sum_{j>1} G_{kj} + \psi_{11} Q_{k1} + \sum_{i>1} \psi_{0i} \psi_{1i} Q_{ki}$$

where:

the load Sd cover :

- The bending moment in span
- The bending moment in central support
- The shear load at the end support
- The shear load on the central support
- The strength capacity on the end support in compression
- The strength capacity on the central support in compression
- The assembly capacity on the end support below a negative loading
- The assembly capacity on the central support below a negative loading

And all this criteria with and without thermal gradient and creep effect

k : statistic coefficient in function of the number of tests done (0.85 if only 1 test etc)

$R_{ad,S}$: cover the corrections in link with the nominal panel (ratio between the measured value and nominal value for f_y, e, t_i, f_{Cc} f_{Cv} etc)

$R_{adj,Bs} = \gamma t \times ([(t_1 / t_{1obs}) + (t2 / t2obs)] / 2) \times (e / e_{obs})^2$
$R_{adj,GcAc} = G_{ck} / G_{cobs} \times (D / D_{obs})$ or alternatively $G_{ck} / G_{cobs} \times (d_c / d_{cobs})$
$R_{adj,Ms} = \gamma t \times (t_2/t_{2obs})^{\beta} \times (f_{y2}/f_{y2obs})^{\alpha} \times (e / e_{obs})$ with alpha and beta following A.5.5.4 EN 14509
$R_{adj,MF1} = \gamma t \times (t_1/t1_{obs})^{\beta}$
$R_{ad,V} = f_{Cvk} / f_{cv,obs} \times (D / D_{obs})$ or in alternative $f_{Cvk} / f_{cv,obs} \times (d_c / d_{cobs})$ or $m_k / m_{,obs} \times (D / D_{obs})$

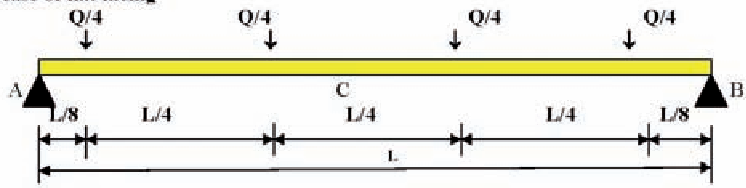
γ_M : material safety factor function of the type of collapse (wrinkling, shear, compression)
$f_{(Q)}$: function is in link with the loading applied (strength of material formula)

X = 200 or 100 etc in function of the use of the panel

Example 1 to 3 of f(Q) at ULS (with Qc) an SLS (with Qel) with the test loading corresponding at 4 loads by span (also possible to do it with two loads by span, UEATC loading)

Test configuration on 2 supports : Beam with 4 loads by span

In case of flat facing



Action on supports

On the left support

$$R_A = \left(\frac{Q}{2}\right)$$

On the right support

$$R_B = \left(\frac{Q}{2}\right)$$

Shear forces

On the left support

$$V_{(x=0)} = \left(\frac{Q}{2}\right)$$

On the right support

$$V_{(x=L)} = -\left(\frac{Q}{2}\right)$$

After the first load load

$$V_{(x=L/8+\varepsilon)} = \left(\frac{Q}{4}\right)$$

After the second

$$V_{(x=3L/8+\varepsilon)} = 0$$

Bending moments

At the first load

$$M_{(x=L/8)} = \left(\frac{QL}{16}\right)$$

At the second load

$$M_{(x=3L/8)} = \left(\frac{QL}{8}\right)$$

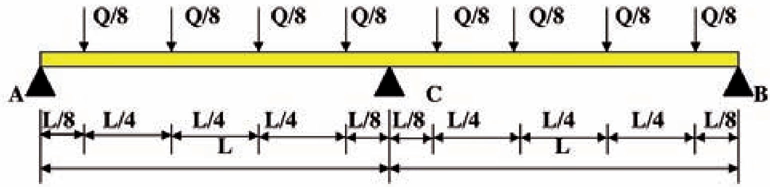
Deflections at mid span

$$f_{(x=L/2)} = \frac{1}{B_s}\left(\frac{41QL^3}{3072}\right) + \frac{1}{G_c A_c}\left(\frac{QL}{8}\right)$$

$$\delta_{(x=L/2)} = \frac{41QL^3}{3072B_s}\left[1+\frac{128K}{41}\right] \text{ with : } K = \frac{3B_s}{G_c A_c L^2}$$

Example 1: panel on 2 supports

Test configuration on 3 supports : – loading L/8; L/4; L/4; L/4; L/8 by span –



$$K = \frac{3B_s}{G_c A_c L^2}$$

Action on supports

On the end support

$$R_A = R_B = \left(\frac{1}{1+K}\right)\left[\frac{95}{512} + \frac{K}{4}\right]Q$$

On the central support

$$R_c = \left(\frac{1}{1+K}\right)\left[\frac{161}{256} + \frac{K}{2}\right]Q$$

Shear forces

On the left support

$$V_{(x=0)} = \left(\frac{1}{1+K}\right)\left[\frac{95}{512} + \frac{K}{4}\right]Q$$

At the load n°1

$$V_{(x=L/8+\varepsilon)} = \left(\frac{1}{1+K}\right)\left[\frac{31}{512} + \frac{K}{8}\right]Q$$

At the load n°2

$$V_{(x=3L/8+\varepsilon)} = -\left(\frac{1}{1+K}\right)\left[\frac{33}{512}\right]Q$$

At the load n°3

$$V_{(x=5L/8+\varepsilon)} = -\left(\frac{1}{1+K}\right)\left[\frac{97}{512} + \frac{K}{8}\right]Q$$

At the load n°4

$$V_{(x=7L/8+\varepsilon)} = -\left(\frac{1}{1+K}\right)\left[\frac{161}{512} + \frac{K}{4}\right]Q$$

Bending moments

At the second load

$$M_{T\max(x=3L/8)} = \frac{QL}{4096}\left(\frac{1}{1+K}\right)[157 + 256K]$$

On the central support

$$M_C = \left(\frac{1}{1+K}\right)\left[\frac{33}{512}\right]QL$$

At mid span

$$M_{T(x=L/2)} = \left(\frac{1}{1+K}\right)\left[\frac{31}{1024} + \frac{4K}{64}\right]QL$$

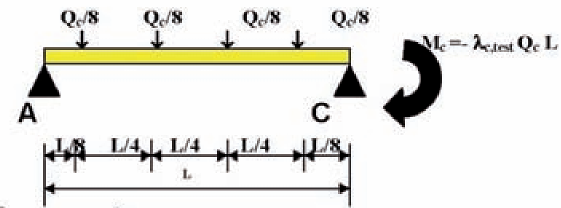
Deflections at mid span

$$f_{(x=L/2)} = \frac{QL^3}{48B_s}\left(\frac{1}{1+K}\right)\left[K^2 + K\left(\frac{169}{128}\right) + \left(\frac{65}{512}\right)\right]$$

$$f_{(x=L/2)} = \frac{QL^3}{96B_s}\left(\frac{1}{1+K}\right)\left[2K^2 + K\left(\frac{169}{64}\right) + \left(\frac{65}{256}\right)\right]$$

Example 2: panel on 3 support (elastic behaviour)

Sandwich beam on 2 supports, 4 loads by span + residual moment at the end support



$$\lambda_c = \left[-\frac{1}{4}+\frac{R_{c,test}}{2Q_{c,test}}\right]$$ **With action on central support R_c measured**

Action on supports

On the end support

$$R_A = Q_c\left[\frac{1}{4}-\lambda_c\right]=\frac{(Q_c - R_c)}{2}$$

On the central support

$$R_C = Q_c\left[\frac{1}{4}+\lambda_c\right]=\frac{R_c}{2}$$

Shear forces

On the left support

$$V_{(x=0)} = Q_c\left[\frac{1}{4}-\lambda_c\right]=\frac{(Q_c - R_c)}{2}$$

Bending moments

On the central support

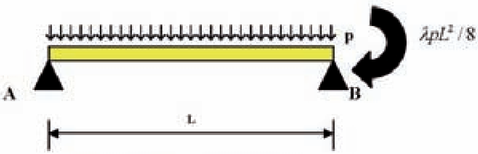
$$M_c = \left[\frac{Q_c - 2R_c}{4}\right]\times L = -\lambda_c Q_c L$$

At 3L/8

$$M_{\max\ in\ span\ (x=3L/8)} = Q_c L\left[\frac{1}{16}-\frac{3\lambda_c}{8}\right]=\frac{5LQ_c}{32}-\frac{3LR_c}{16}$$

Example 3: panel on 2 supports with residual bending momen (elastic-plastic approach)

Sandwich beam on 2 supports, uniform loading + residual moment at the end support



Actions on the supports

On the left

$$R_A = \frac{pL}{2} - \frac{\lambda pL}{8}$$

On the Right

$$R_B = \frac{pL}{2} + \frac{\lambda pL}{8}$$

Shear forces

$$V_{(x)} = \frac{pL}{2} - px - \frac{\lambda pL}{8} \quad \text{max in } x = \left(\frac{L}{2} - \lambda\frac{L}{8}\right)$$

Bending moments

$$M_{(x)} = \frac{pL}{2}x - \frac{px^2}{2} - \frac{\lambda pL}{8}x \quad \text{max in } x = \left(\frac{L}{2} - \lambda\frac{L}{8}\right)$$

$$M_{F(x)} = \left(\frac{Lx}{2} - \frac{x^2}{2} - \frac{\lambda Lx}{8}\right)(1-\beta)p \qquad M_{F\max} = \frac{pl^2}{16}\left(2 - \lambda + \frac{\lambda^2}{8}\right)(1-\beta)$$

$$M_{F1(x)} = \left(\frac{Lx}{2} - \frac{x^2}{2} - \frac{\lambda Lx}{8}\right)(1-\beta)p \qquad M_{F1\max} = \frac{pl^2}{16}\left(2 - \lambda + \frac{\lambda^2}{8}\right)\beta$$

$$\beta = \frac{B_{F1}}{\left[B_{F1} + \dfrac{B_s}{\left(1 + \left[\dfrac{16}{5-3\lambda}\right]K\right)}\right]} \qquad K = \frac{3B_s}{G_c A_c L^2}$$

Deflections at mid span

$$\delta_{s(x=L/2)} = \delta_{F1} = \frac{pL^4}{384\,B_s}(5-3\lambda)\left(1 + \left(\frac{16}{5-3\lambda}\right)K\right)(1-\beta)$$

$$\delta_{s(x=L/2)} = \frac{5pL^4}{384\,B_s}(1-\beta) - \frac{\lambda pL^4}{128B_s}(1-\beta) + \left(\frac{pL^2}{8G_cA_c}\right)(1-\beta)$$

Example of Sd (q) for load table

The design by testing procedure is as follows:

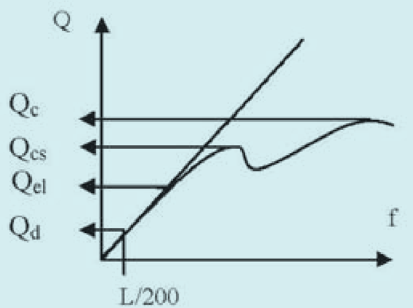
Performance of large scale tests

On small, intermediate and max span of the panel range

On minimum, intermediate and maximum thickness

- Positive loading: 2 supports (A7 or A8 EN 14509) and 3 supports (UEATC/EASIE)
- Negative loading: 2 supports (A7 or A8 EN 14509) and 3 supports (UEATC/EASIE) (Panel fixed on supports)
- Reaction to support test (A15 EN 14509)
- Eventual thermal tests or use of k1 coefficient EN 14509

The results are the curves load-displacement and eventual action on the central support (end supports)



And carried out the small tests on the samples/ use CE marking results to find $f_{Cc};f_{Cv};f_y;G$; m ...

Determination of the bending and shear rigidities B_s; (B_{F1}) and G_cA_c

- By calculations (EN 14509)

or

- By solving couple of deflection equations where (Qd, f, Rd) Known, and the rigidities unknown

or

- Or span by span (deflection and action on central support known)

Determination of the strength capacities at ULS ($M_{U,Rd}$, $V_{U,Rd}$, $F_{U,Rd}$) based of the use of the large scale test results:

$$S_{U,Rd} = k \times R_{ad} \times \frac{f_{(Q_c)}}{\gamma_M}$$

- in elastic (maximum load inferior at the load of wrinkling on central support (Q_{cs})
- in elastic-plastic (rest moment on central support after wrinkling on central support, collapse load used (Q_c)

Determination of the strength capacities at SLS ($M_{E,Rd}$, $V_{E,Rd}$, $F_{E,Rd}$) based of the use of the large scale

$$S_{E,Rd} = k \times R_{ad} \times \frac{f_{(Q_{el})}}{\gamma_M}$$

- in elastic (maximum load in the linear part of the curve load displacement (Q_{el}/Q_{dp})

Determination of the load/ span tables:

- Combination at ULS and SLS of self weight, and outside load (wind, snow, thermal gradient, creep) to determine $S_{U,Sd(qi)}$ and $S_{E,Sd(qi)}$

  $S_{U,Sd}$ = ($M_{U,Sd}$, $V_{U,Sd}$, $F_{U,Sd}$) and $S_{E,Sd}$ = ($M_{E,Sd}$, $V_{E,Sd}$, $F_{E,Sd}$)

- $S_{U,Sd(qi)} \leq S_{U,Rd}$ (from the test results corrected)
- $S_{E,Sd(qi)} \leq S_{E,Rd}$ (from the test results corrected)
- $w_{Ed} < L/X$ at SLS

5

Use of sandwich panels for stabilisation of buildings and building components

Sandwich panels are traditionally used as covering and isolating components of building, thus being secondary structural components of the building. The panels are mounted on a substructure and they transfer transverse loads, e.g. wind and snow, to this substructure.

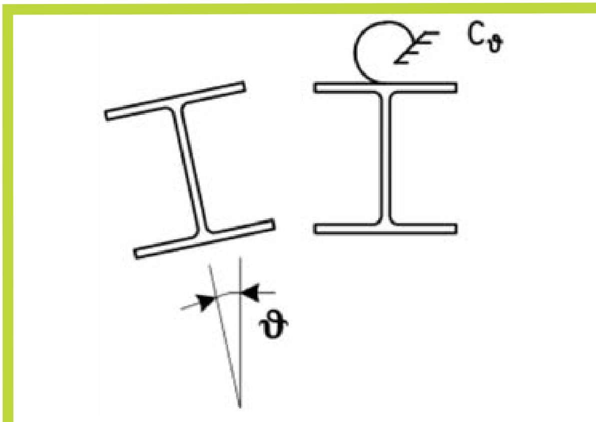
But sandwich panels have also stabilising effects on the substructure: Sandwich panels increase the resistance of building components (beams and columns) against lateral torsional buckling by torsional restraint. The high in-plane shear resistance of sandwich panels can also be used for stabilising effects. Buckling and lateral torsional buckling can be prevented by re-straint of lateral displacement. Furthermore sandwich panels can be used for global stabilisation of buildings against horizontal loads. The panels transfer horizontal wind loads and thus replace wind bracings.

Torsional restraint

Sandwich panels increase the resistance of substructures (beams, purlins) against lateral torsional buckling by restraining rotations and lateral displacements.

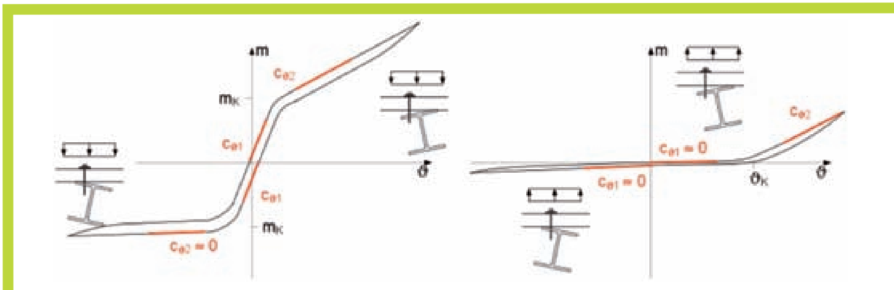
The torsional restraint is governed by the stiffness of the connection of the sandwich panel to the substructure. Research carried out at the University of Karlsruhe has shown that this stiffness significantly depends on the transverse load transferred by the sandwich panel.

The torsional restraint can be taken into account for the design of beams and purlins. This is done by a rotational spring, which prevents rotation of the beam around the longitudinal axis.



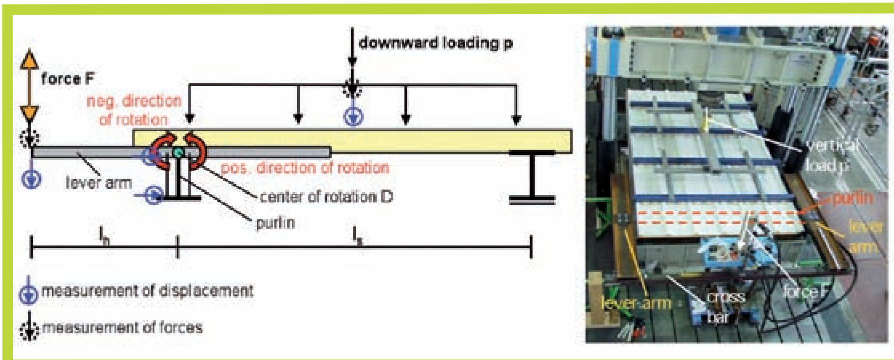
Stabilisation of a beam by torsional restraint

The stiffness of this rotational spring is a combination of the bending stiffness of the attached panel, the stiffness of the connection and the distortional stiffness of the beam to be stabilised. The bending stiffness of the panel and the distortional stiffness of the beam can be determined comparatively easily. The stiffness of the connection was part of the investigations done within the framework of workpackage 3 of the EASIE project. A mechanical model for determination of the moment-rotation relation was developed.



Moment-rotation-relation for downward and uplift loading

To determine all parameters of the moment-rotation relation tests and additional numerical investigations were performed.

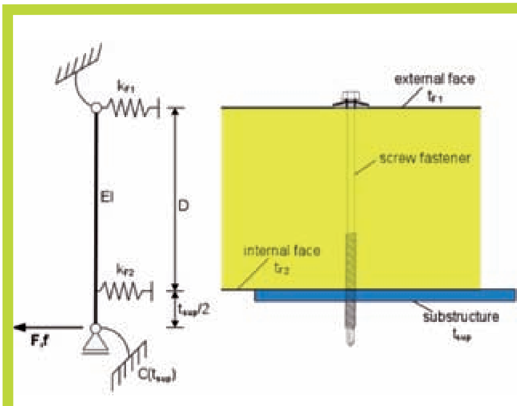


Test set-up for downward loading

The formulae apply for sandwich panels with facings made of steel, aluminium or GFRP and with cores made of polyurethane, EPS or mineral wool. The influence of different kinds of connections (fixings through lower and through upper crimp, fixings with calottes) has also been investigated. Also the effects of long-term loads and elevated ambient temperature were included in the developed model.

In-plane shear stiffness

When loaded by in-plane shear forces, sandwich panels have a high stiffness. The high in-plane shear stiffness can be used for two different stabilising effects. Sandwich panels can restrain the lateral displacement of beams and columns and prevent flexural and lateral torsional buckling. By acting as diaphragm sandwich panels can also be used for global stabilisation of complete building structures and for transferring horizontal loads, e.g. wind loads. If sandwich panels are used for transferring horizontal loads, they can replace wind bracings.



Mechanical model of a fastening

The in-plane shear stiffness of sandwich panels is very much higher than the stiffness of the fastenings. The same applies for the load-bearing capacity. So to make use of the potential presented by in-plane shear loaded panels, knowledge of stiffness and resistance of the fastenings is mandatory. Within the framework of workpackage 3 of the EASIE project a mechanical model for fastenings of sandwich panels has been developed.

Stiffness and load-bearing capacity of a fastening are influenced by different single components. In the mechanical model these components are replaced by longitudinal or rotational springs. For determination of stiffness and load bearing capacity of the springs various tests have been performed and evaluated. Finally a generalised calculation procedure for the stiffness of direct fastenings of sandwich panels was developed.

A calculation procedure for determination of the stiffness of shear diaphragms made of sandwich panels was developed in a former research project by Baehre and Ladwein. Based on this model, calculation procedures for determination of the forces of fastenings, which are decisive for the load bearing behaviour and capacity of shear loaded sandwich panels, were developed within the EASIE project. Transfer of horizontal loads and global stabilisation of buildings was considered as well as stabilisation of single building components (beams and col-umns).

Further information

Further information on the stabilising effects of sandwich panels as well as some calculation examples can be found in the following reports, which are part of the deliverables of the EASIE project and can be downloaded at www.easie.eu:

- Deliverable D3.3 – part 1: Stabilisation of beams by torsional restraint
- Deliverable D3.3 – part 2: In-plane shear resistance of sandwich panels
- Deliverable D3.3 – part 3: Stiffness and load bearing capacity of shear loaded fastenings of sandwich panels

Furthermore different papers on this topic were published:

- Misiek, Th., Käpplein, S., Dürr, M., Saal, H.: "Stabilisation of purlins by sandwich panels – new regulations and recent research results", CIB World Congress 2010. Proceedings (www.cib2010.org/post/files/papers/462.pdf).
- Käpplein, S., Misiek, Th., Ummenhofer, T.: "Aussteifung und Stabilisierung von Bauteilen und Tragwerken durch Sandwichelemente (Bracing and stabilisation by sandwich panels)", Stahlbau, Vol. 79, No. 5, pp. 336-344, 2010 (in German).
- Käpplein, S., Ummenhofer, T.: "Querkraftbeanspruchte Verbindungen von Sandwichele-menten (Shear loaded fastenings of sandwich panels)", Stahlbau, Vol. 80, No. 8, 2011 (in German).
- Misiek, Th., Käpplein, S., Saal, H., Ummenhofer, T.: "Lateral torsional stabilization by sandwich panels", eurosteel 2011.
- Baehre, R., Ladwein, Th.: Tragfähigkeit und Verformungsverhalten von Scheiben aus Sandwichelementen und PUR-Hartschaumkern (Projekt 199). Studiengesellschaft Stahlanwendung e.V., Düsseldorf 1994.

Design of frameless structures made of sandwich panels

6

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. As a recent development, sandwich panels are used to design small buildings– such as cooling chambers, climatic chambers and clean rooms – without any load-transferring substructure. In this application the panels are not only used as cladding element but also for load transfer and bracing of the building.

Building made of sandwich panels but without load-bearing substructure

Axially loaded sandwich panels

In addition to the moments and transverse forces resulting from transverse loads, the wall panels of frameless buildings transfer normal forces arising from the super-imposed load from overlying roof or ceiling panels. This raises the question of the load bearing behaviour and the load bearing capacity of sandwich panels subjected to axial load or a combination of axial and transverse load.

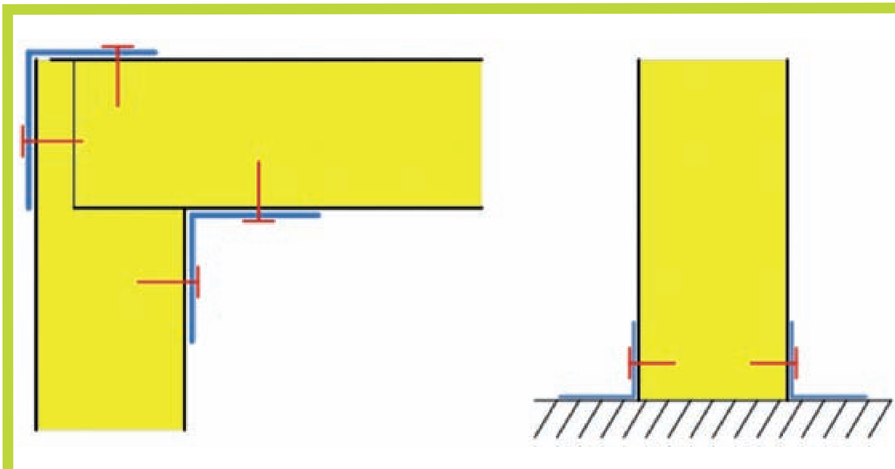
Within the framework of workpackage 3 of the EASIE project, design methods for axially loaded sandwich panels have been developed. The design model is based upon the existing design model for panels subjected to transverse loads according to the EN 14509 standard. Buckling tests and numerical investigations have shown that panels subjected to axial loads can be designed according to 2nd order theory with the conventional amplification factor α. The wrinkling stress determined in simple bending tests can be used as ultimate stress.

Furthermore the behaviour due to long-term loads (creeping of the core material) can be considered by the design method. Only the creep coefficients, which are also used for the design of panels subjected to transverse loads, have to be known. For verification long-term tests on axially loaded sandwich panels were performed.

Buckling and long-term test on axially loaded sandwich panels

The design method has the advantage that there is no necessarily of any additional test. To design axially loaded sandwich panels only the parameters used for the design of panels subjected to transverse loads have to be known (e.g. wrinkling stress and creep coefficients).

In addition to the global load-bearing behaviour the local load-bearing capacity at the areas of load application, i.e. at the lower ends of the panel and at the connection between wall and ceiling, where the superimposed loads from the ceiling are applied as normal force to the wall panels, is to be considered. The load-application areas have been investigated by tests and numerical calculations. A calculation procedure for determination of the local strength has been developed.

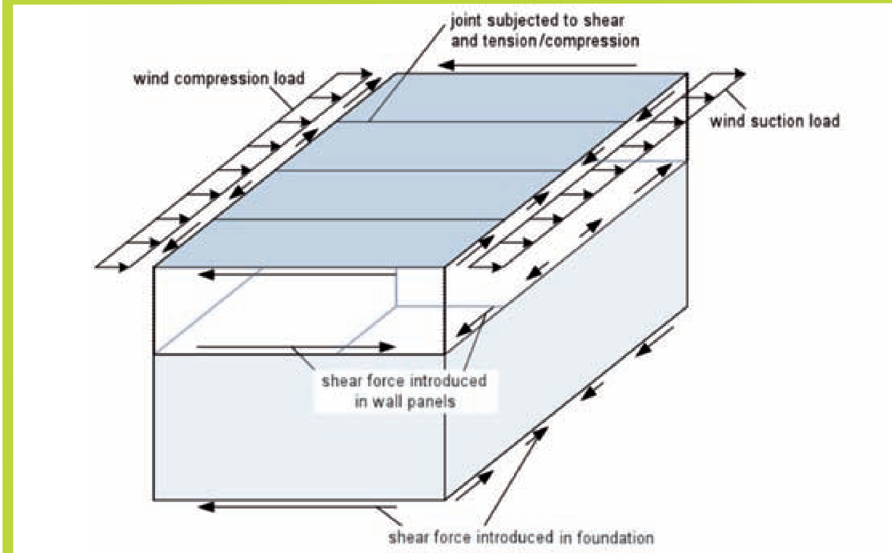


Connection between wall and ceiling and lower end

Bracing of the building

If sandwich panels are used without load-transferring substructure, the panels have to transfer horizontal wind loads to the foundation and to stabilise the building. For this purpose the high in-plane shear stiffness and capacity of the panels is used. Both, stiffness and load bearing capacity are very much higher than the corresponding values of the fastenings. Because of that for design purposes the deformation of the panels can be neglected. Only the flexibility of thefastenings has to be considered. Also for the load-bearing capacity the fastenings are decisive. Thus, if a frameless structure is loaded by horizontal wind loads, the fastenings have to be designed for this load.

Within the EASIE project basic principles for the design of frameless structures for the transfer of horizontal loads have been worked out. Calculation procedures for determination of the for-ces the fastenings have to be designed for were developed.



General principle of transfer of horizontal wind loads in a frameless structure

Further information

All investigations on frameless structures, which were done within the framework of the EASIE project, can be found in the following reports:

- **Deliverable D3.3 – part 4:** Design of axially loaded sandwich panels; global load bearing behaviour
- **Deliverable D3.3 – part 5:** Design of axially loaded sandwich panels; load bearing behav-iour of load application areas
- **Deliverable D3.3 – part 6:** Transfer of horizontal wind loads and stabilisation of frameless structures

In addition a Design Guideline (Deliverable D3.4) for the application of the design formulae was prepared. The Design Guideline also includes some calculation examples.

All these documents can be downloaded at www.easie.eu.

Furthermore the following papers dealing with axially loaded sandwich panels were published:

- Käpplein, S., Ummenhofer, T.: "Axial beanspruchte Sandwichelemente in rahmenlosen Konstruktionen (Axially loaded sandwich panels in frameless buildings)", Stahlbau, Vol. 79, No. 10, pp. 761-770, 2010 (in German).
- Käpplein, S., Ummenhofer, T.: "Classification of stability failure modes of sandwich panels under compression loading: global and local buckling, crippling at support line", Procee-dings of SDSS, International Colloquium Stability and Ductility of Steel Structures, pp. 1033-1040, 2010. (www.labciv.eng.uerj.br/sdss2010/files/sdss_rio_2010_11_17.pdf).

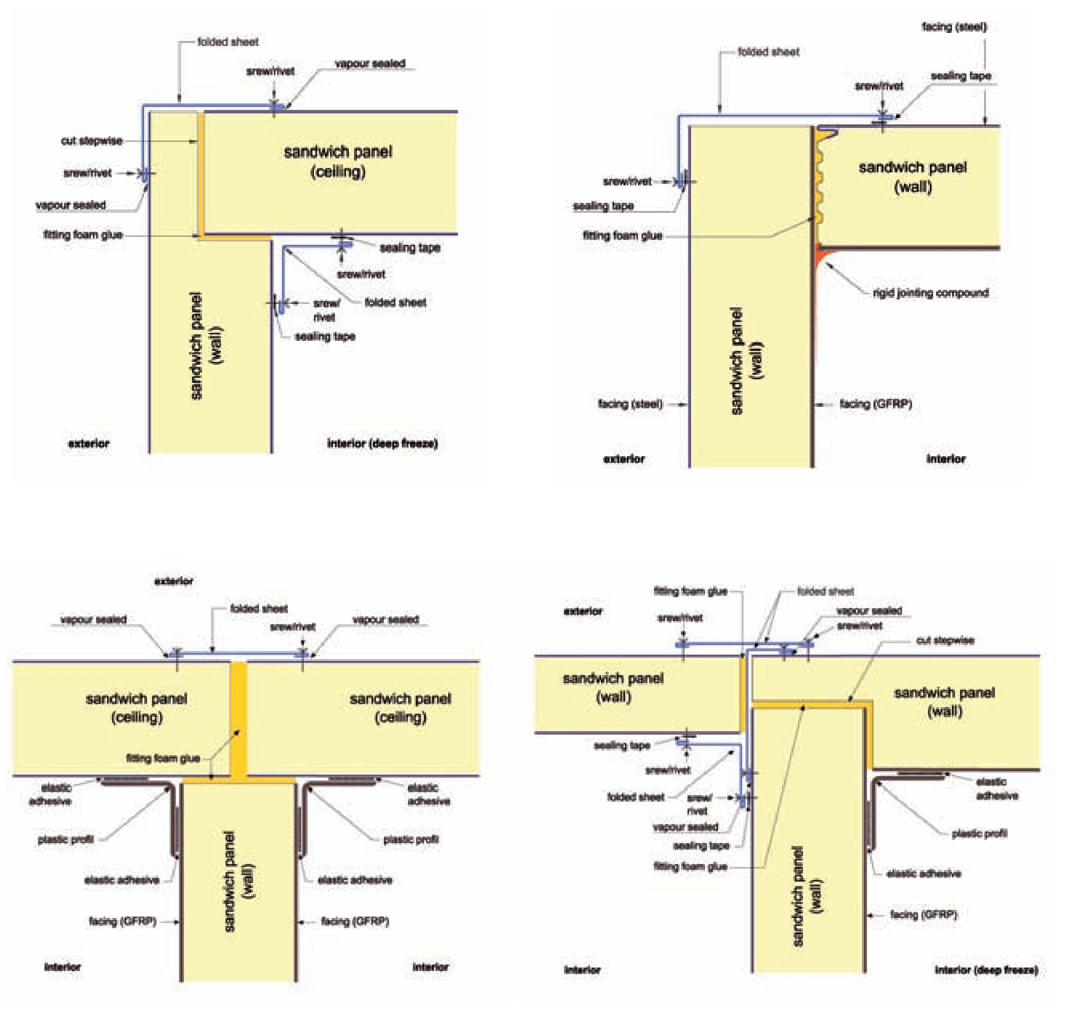
7

Guideline for construction good practice of frameless buildings

The design concept of a frameless building made of sandwich panels is presented here together with the constructional details of the panel connections. This is largely based on the substantial collective experience of the EASIE partners and in particular the panel manufacturers

Experiments and model calculations have determined the scale of axial load bearing capacity and in-plane shear resistance. It has been shown that sandwich panels have load bearing capacity which is more than adequate for usual stresses. The way in which the force is applied has been shown to be significant. It was experimentally demonstrated with small scale tests and practically by using a demonstrator that panel connections according to known principles in the common use of sandwich panels, as applied in the construction of cold rooms, machine enclosures, etc., are generally suitable for pure sandwich construction of small building structures. The guide provides a structured series of design examples for the components to be connected (roof / ceiling, wall, floor). Facing material specific features and building climate aspects are taken into account.

Demonstrator



Details (examples)

8 New techniques to maintain and repair sandwich panels systems

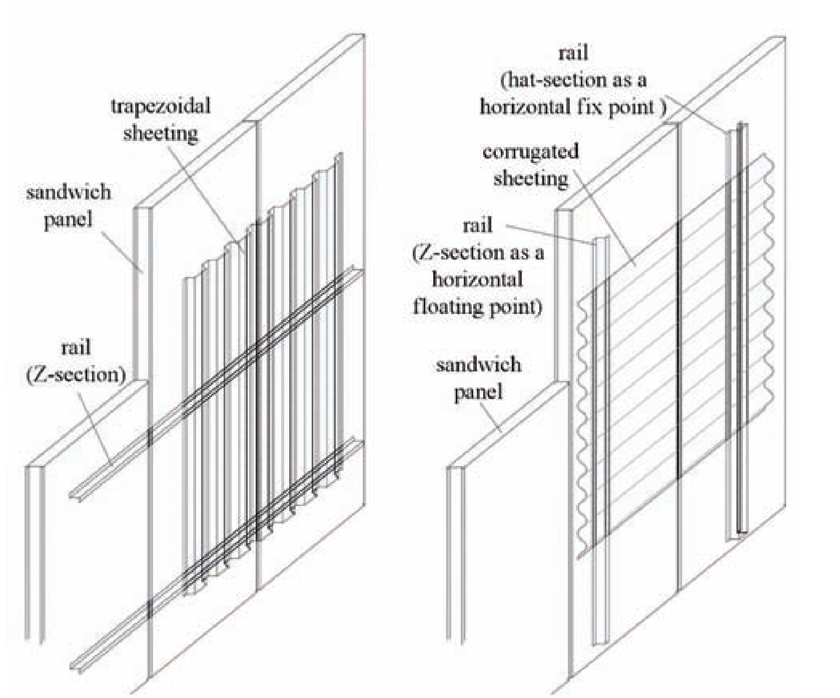
Material ageing or damage or the need to improve the performance or appearance or to extend the service life of the building may require the repair 0f sandwich panels. This may mean cleaning or painting of the surfaces, fixing the joints and sealants or repairing the structural parts of the façade and roof.

In EASIE conventional cladding systems based on thin-walled purlins and sheetings and new systems based on additional sandwich elements or monopanels have been studied.

Cladding changes the loads and the static behaviour and resistance of the wall and roof structure consisting now ordinary sandwich panel to which have been added additional components and elements.

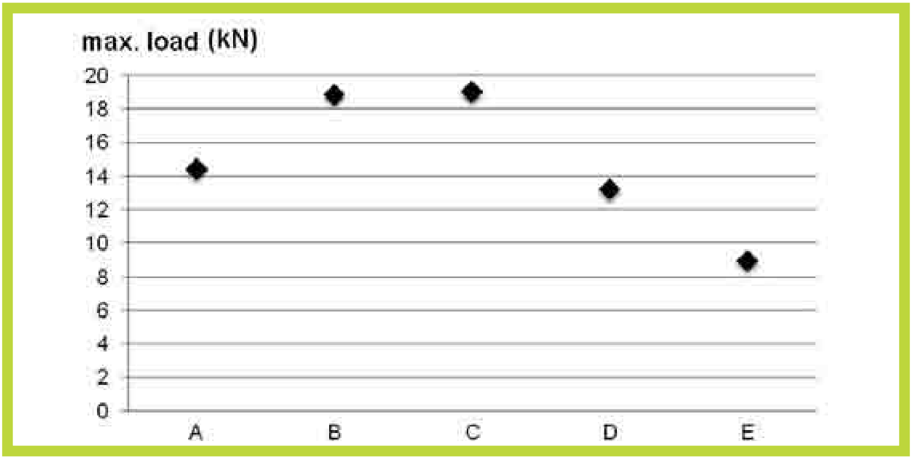
Guidelines have been produced for the design and installation of cladding systems based on the study of conventional system based on purlins in parallel or transverse direction to the span and on trapezoidal sheetings and cassettes and on a new system based on additional sandwich panels or monopanels consisting of the external face and a core layer only.

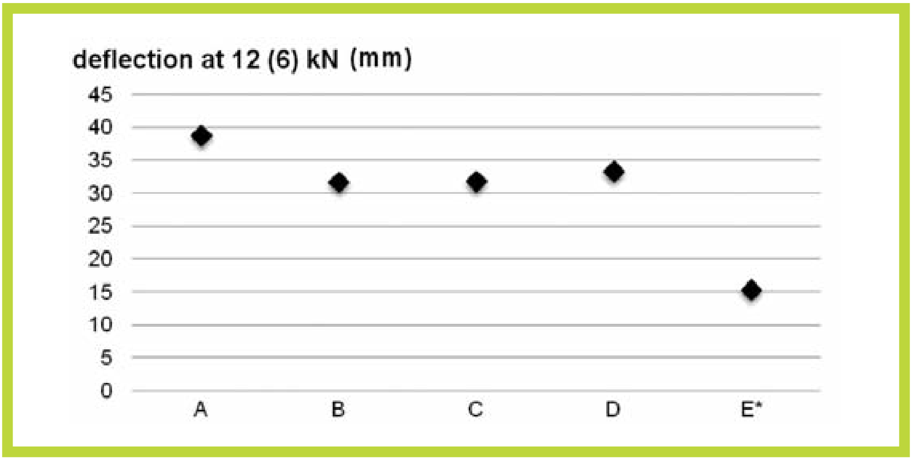
Compared to the initial tests, panels with hat-profiles in longitudinal direction and sinusoidal sheet mounted directly on the face of the panel resulted in a high load-bearing capacity. The Z-profiles led to a loss of the load-bearing capacity because of



the local compression caused by the edge of the profile into the face of the sandwich panel.

The figure below shows the deflection of the panel to the load of 12 kN (6 kN in the case of panels with the transversal Z-profile which did not reach this load level). The deflection was proportional to the load in all tests.



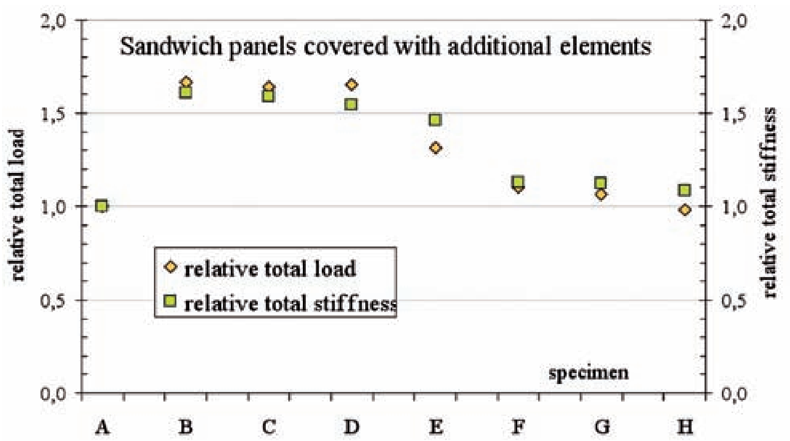


*The deflection E (Z-profile) is given for a load of 6 kN.

A : initial test (l=4000 mm)
B : sinusoidal sheet without purlin (l=4250 mm)
C : hat-profile in longitudinal direction (l=4250 mm)
D : hat-profile in transverse direction (l=4250 mm)
E : z-profile in transverse direction (l=4250 mm)

In addition to the full scale tests, small tests were carried out to determine the stiffness of the connection between face and cladding. In the tests, a piece of the sinusoidal sheet was mounted on the sandwich-panel in the same way as in the full scale tests and loaded in its longitudinal direction. The stiffness of the connection can be taken from the load-deflection curve. Because of low results no test were performed for the Z-profile-connection.

specimen	c (N/mm)
hat-profile in longitudinal direction	5875
sinusoidal sheet without purlin	3086
hat-profile in transverse direction	540



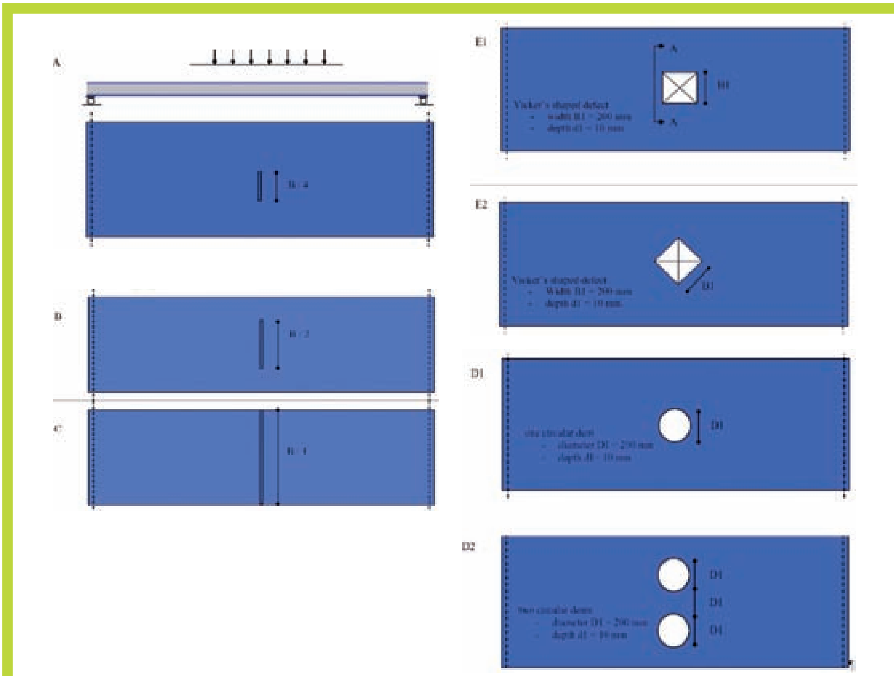
A : ordinary sandwich panel D = 100 mm
B : ordinary sandwich panel + additional panel D = 40 mm, IR2-4.8 screws c/c 300 mm
C : ordinary sandwich panel + additional panel D = 40 mm, IR2-4.8 screws c/c 500 mm
D : ordinary sandwich panel + additional panel D = 40 mm, SL-2 screws c/c 500 mm
E : ordinary sandwich panel + additional panel D = 40 mm, SL-2 screws c/c 1000 mm
F : ordinary sandwich panel + additional monopanel D = 40 mm, IR2-4.8 screws c/c 300 mm
G : ordinary sandwich panel + additional monopanel D = 40 mm, IR2-4.8 screws c/c 500 mm
H : ordinary sandwich panel + additional monopanel D = 40 mm, IR2-4.8 screws c/c 1000 mm

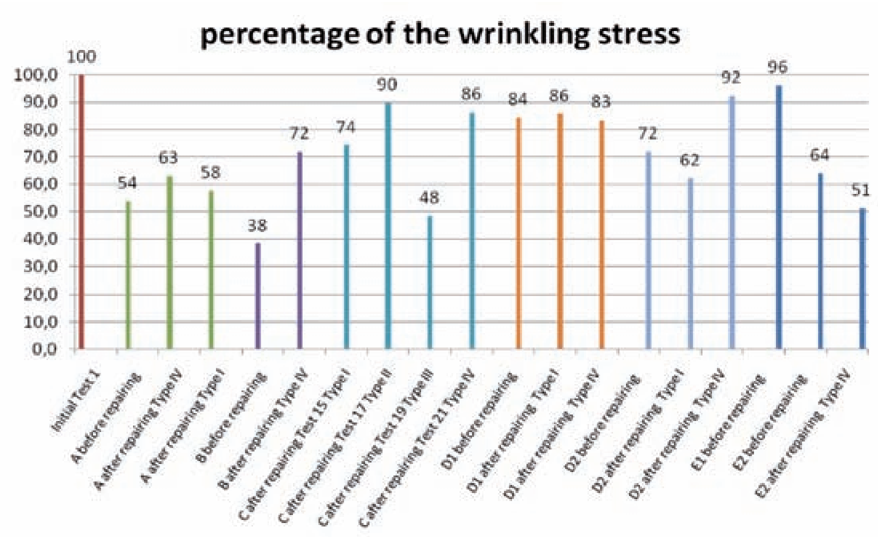
Comparison of the experimental load-bearing capacity (total load) and stiffness (change of the load to the change of the mid-span deflection) of the full-scale specimens with different cladding elements and fastenings to the ordinary three-layer sandwich panel shows potential benefits of the new cladding systems in term of mechanical behaviour.

The experimental results relate to the span (4 m) and depth (100 + 40 mm) of the specimen. The components of the cladding system were assembled with screws and rivets fixed between two thin-walled components or elements. Gluing may be another promising way to fix the additional components to the external face of the wall and roof panel.

The benefits of the adhesive joints are the invisible fastenings and fluent flow of stresses without stress concentrations between the components. The gluing in outdoor conditions requires careful cleaning and preparation of the contact surfaces. The working temperature and humidity may be limited to a narrow range and a prestressing of the joints is needed for a time during the hardening of the adhesive. The gluing systems have to be tested to withstand service conditions.

In the EASIE project, different techniques have been studied in order to return totally or partially the resistance of the sandwich panel having defects in their external face. Repairs are normally carried out outdoor which puts additional demands on the technique. In the study all panels have been repaired in a horizontal position rather than the vertical position usual for wall panels. Seven different damage patterns have been used to simulate the defects caused by a wrinkling or a crash. Damage patterns A, B and C were caused by cutting and pressing in the upper layer sheet. The width of the cut was a quarter (A), a half (B) or the whole width (C) of the panel. Damage pattern D1 and D2 were made by pressing a steel ball into the panel and the damage pattern E1 and E2 using a steel pyramid impacter.





Four different types of materials were used for the reairs (types I, II, III and IV). In principle, it is possible to repair cuts (A, B, C) by using a selected material and procedure and thereby improve the load bearing capacity. None of the materials used in the study resulted in the returning of the strength totally to the level of the initial wrinkling stress. The repairs of the dents (D1, D2, and E2) resulted in no improvements with panels being worse than when using an improper repairing procedure.

Further information

Further information on sandwich panels repair and retrofitting can be found on the project website at www.easie.eu

For additional details on the repair technique developed within EASIE see the website of RBM Europe BV.

Publications:

- P.Hassinen, T.Misiek and B.Naujoks "Cladding systems for small panels, refurbishment of walls and roofs", EUROSTEEL 2011, August 31st-September 2nd 2011, Budapest.
- P.Hassinen, T.Misiek and B.Naujoks "Fassadensysteme zur Sanierung von Wänden aus Sandwichelemente ", Stahlbau 9, September 2011 (In German)

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www.easie.eu

Research areas on sandwich panels technology	Sandwich panels : Project Partners	Sandwich panels	E-learning based education on sandwich panels	Library & tools	News
Results of the EASIE research	19 partners (industries, universities, industrial associations) from 10 different European countries have been involved in the project	Manufacturing Official documents	E-learning lectures on sandwich design and application	Information about sandwich technology in construction	10 e-letters

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Invitation Workshop June 9th 2011 - Krakow-Poland

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Sandwich Panel European collaborative project

Seventh Framework Programme

Ensuring Advancement in Sandwich Construction through Innovation and Exploitation

The EASIE project has received financial support from the European Community's Seventh Framework Programme FP7/ NMP2-SE-2008 under grant agreement No 213302.

Sandwich panels are modern lightweight building components used to cover walls and roofs of buildings and to isolate spaces inside buildings. They are typically made of two thin metal sheets with an insulating core between the faces.

The use of sandwich panels is continuously increasing and new application areas are opened in industrial, residential and office buildings. The European Standard for sandwich panels EN 14509 has a lack of rules or requirements for many important areas like fastening of the panels, openings in panels, axially loaded panels and panels stabilizing frame structures. Despite there is a lot of knowledge in different countries on these subjects, no common rules have been developed, thus putting a hinder to the standardisation and leading to barriers for some of these applications.

The aim of this project is to overcome these problems and develop solutions and technical guidelines ready for implementation for the revision of the standard EN 14509 published in December 2008.

The second goal of the project is to implement the new information in the use in practice, which will be carried out through seminars and practical guidelines as well as e-learning modules. The subjects are of high industrial and user interest. The project introduces guidelines for topics not included in the present version of the standard but will on the base of this research be implemented in a later revision of the standard. The subjects are very important in practice. Practical guidelines and seminars will help and broaden the correct and safe use of sandwich panels in Europe and ICPC. The innovative parts of the project are new applications like the in-plane shear and axial resistance.

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16 e-learning lectures are available on www.easie.eu

- **Load Bearing Behaviour. How is a sandwich panel working**

  Comportamiento de los paneles bajo carga. ¿Cómo trabaja un panel sándwich? (Spanish version)

  Jak działa płyta warstwowa - zachowanie pod obciążeniem (Polish version)

  Prof. Dr.-Ing. Jörg Lange - TU Darmstadt, Germany

  Dipl.-Ing. Aneta Kurpiela - TU Darmstadt, Germany

- **Actions and loads. Special Aspects of Sandwich Structures**

  Oddziaływania i obciążenia. Specjalne aspekty dla płyt warstwowych – Prof. dr inż. Klaus Berner - iS engineering, Niemcy (Polish version)

  Prof. Dr.-Ing. Klaus Berner - IS Mainz, Germany

- **Allowable span tables on the base of the CE-mark**

  Tablas de carga con los datos del nuevo marcado CE (Spanish version)

  IS- Prof. Dr.-Ing. Klaus Berner - IS Mainz, Germany

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Detailing

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The EASIE project has received financial support
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