

Methods to Measure the Durability of Structural Sandwich Panels

Hassinen, P.

Aalto University Department of Structural Engineering and Building Technology, Finland
(email: paavo.hassinen@tkk.fi)

Pfeiffer, L.

ThyssenKrupp Steel Europe AG Profit Center Color/Construction, Germany
(email: lars.pfeiffer@thyssenkrupp.com)

Abstract

Determination of the intended length of the service life is an increasingly important question and may be soon a crucial parameter in the development and design of civil engineering structures. Length of the service life may be limited by a reduction of the resistance or by an unsatisfactory function at the serviceability state. To determine the service life, knowledge about the deterioration mechanism and their influence on the structural behaviour is needed. In some cases, information about the development of the mechanical and environmental loads during the service life is important, too.

European standard EN 14509 introduces experimental methods to measure the changes of the self-supporting sandwich panels and further, to classify the panels to be fit for the use in external walls and roofs. The methods are based on an indirect parameter by measuring the changes of the cross panel tensile strength and not the properties, which are directly used in the analysis and in design. Ageing of the cross panel tensile test specimens is based on accelerated ageing histories using a high temperature and moisture. The method is practical and relatively easy to use, however, it does neither tell about the changes caused by a real natural environment nor the real changes of the ultimate resistance or the function at the serviceability limit state.

The contribution introduces the parameters which are essential in structural design and then, studies the possibilities to measure the changes of the parameters in long-term use. The essential parameters are the wrinkling strength of a face under compressive stresses and the shear strength of the core and bond. These are followed by a number of other failure modes, such as the resistance at the supports to pressure and suction loads. The information is based on tests with small-scale specimens, the results of which will be compared to a limited number of results on full-scale specimens having been in service and exposed to natural ageing conditions. The contribution concludes the promising possibilities and draws outlines for development of methods for the use in practice.

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1. Introduction

1.1 Definition of a sandwich panel

Sandwich panels in the context of this report are composite structures, consisting of a minimum of two deck layers and a core. The term “panel” is derived from the Latin, French and Dutch word “paneel” and means “a flat piece of construction” (Brockhaus, 1991, a). This describes the general shape of a sandwich panel. The word “sandwich” describes generally a combination of different layers (Brockhaus, 1991, b). A typical sandwich layer in construction consists of three layers. A rather thick rigid core material is laminated between two thin faces. There are many possible combinations of facing and core materials, depending on the intended use of the sandwich panel. This work, however, deals primarily with the most common form of a sandwich panel used currently in the building construction: factory made engineered elements, consisting of thin metallic facings of a thickness between 0.4 and 0.75 mm and rigid foam or inorganic wool core.

1.2 Load bearing behaviour of a sandwich panel

The individual layers of sandwich panels by themselves have almost no load-bearing capacity. In a sandwich panel the layers no longer act separately but are connected in a process of adhesion. Only this rigid connection makes the structure a sandwich panel and increases the load-bearing capacity substantially.

While the metal sheet facing alone is almost without bending capacity as is the core by itself, the connection of the three layers creates a completely new composite structure with widely enhanced capacities. The composite sandwich panel possesses substantially higher load-bearing capacities with regard to bending, shear and torsion impact than the sum of its individual components.

Compared to the metal faces, the core in a sandwich panel generally possesses very limited tension or compression stiffness. The bending moment is therefore distributed to the two faces. For a single span, three-layer sandwich panel loaded by a distributed load, this leads to compression and tension in the two faces that are kept apart at a fixed distance by the core.

Based on the properties of the layers and the distribution of the internal stresses, the core carries through almost all of the shear force. Additionally, the core provides foundations to the faces of the sandwich panel. Because of that, the properties of the core have a significant influence on the overall performance of the sandwich panel and need to be carefully evaluated in sandwich panel design. Losses in the stiffness and strength of the core have immediate influences on the performance of the whole panel. Such losses can, for example, be caused by durability related degradation.

1.3 Durability of construction products

A survey by Sarja (2002) on the typical share of civil engineering products for European countries shows that:

- Civil engineering products represent about 70 to 80% of the national assets.
- The energy use for these products during production and maintenance is about 40% of the total national energy consumption.
- Civil engineering products produce about 35% of the total waste.

These figures emphasise the enormous economical importance of civil engineering products for the societies. Due to the importance and costs of these products, it becomes obvious that there are high demands to the service ability during the life span of the investment.

Economical effects are dominated by the fact that buildings generally require large investments. The expectations in the investment can only be fulfilled if the building keeps its functionality over a certain time period. The estimated time period depends on the type of building. For an industrial building like a warehouse, for example, it is generally assumed that the building is designed for a service period of 25 to 30 years. After this period a substantial refurbishment of the building is generally required.

The most important technological influence for a civil engineering product is the guarantee of the safe use over a time. Building materials need to be designed in a way, which guarantees an adequate structural performance. If a structural building material cannot resist against the received load impacts, the building is damaged or may even collapse. In a worst case scenario, this may lead to a loss of lives and properties. Therefore, the main task in the regulation is to ensure an adequate structural performance of the building materials throughout the whole life cycle of the structure. Legally binding design procedures, which are very much harmonized across Europe, are the base to guarantee a safe structural performance. For sandwich structures, such procedures are defined in the European standard on sandwich panels EN 14509, where also requirements towards the durability of the sandwich panels together with experimental evaluation procedures are described.

In practice, requirements to the fitness for use and to the withstanding the extreme actions during the use are set down to a structure. The previous requirement defines the serviceability limit state and the latter one the ultimate limit state. The structure shall maintain the properties in its environment during its design working life, which defines the requirements on the durability of the structure. The durability requirements may be achieved by choosing correct materials and manufacturing techniques. As a result, the deterioration of the structure will stay small enough or the function and resistance will be guaranteed by regular inspections and refurbishment. In constructions, the first principle is used in the major cases of structures.

The available durability tests give information about the changes of the strength on a macroscopic level without explaining the physical and chemical mechanisms affecting the deterioration of the material. It is believed, that the durability test is able to classify if the product is to fit for the purpose

or not. The durability test methods and the loading histories are therefore strongly dependent on the application.

2. Durability of sandwich panels

The European standard, EN 14 509, makes in chapter 5.2.3 a statement concerning durability; “Durability and other long term effects.” Detailed information on testing scenarios are written down in the normative annex B, “Durability testing method for sandwich panels.”

Currently, the durability performance is only evaluated qualitatively. This means that the loss in cross panel tensile strength under an artificial, durability accelerating climate must stay within certain boundaries over a time. The cross panel tensile strength is seen as an indicator for over all panel performance. Depending on the type of degradation pattern (Fig 1), a core material is either fit for the application or not. The boundaries chosen for an acceptable loss of the strength are, however, lacking the scientific foundation. Even a loss of 60% of the initial tensile strength can be acceptable in accordance with the standard. In particular, such a loss in the tensile strength is allowed without any impact on other relevant design parameters. Because it is not possible to determine the remaining wrinkling stress after the artificial ageing of the tensile strength, a new small-scale test to study the development of the wrinkling stress is developed.

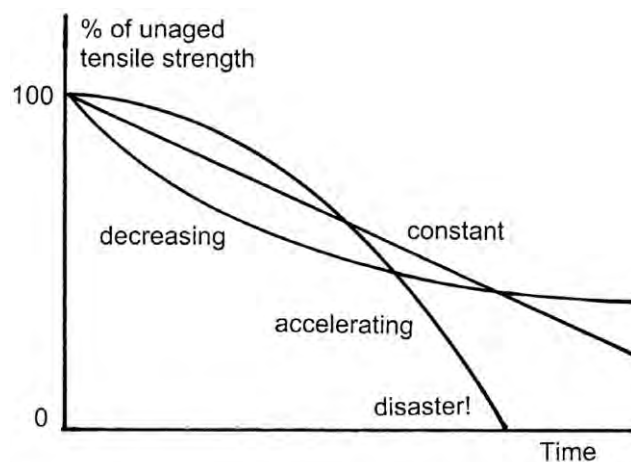


Figure 1. Possible degradation patterns for tensile strength (Davies et al.).

3. Wrinkling stress of sandwich panels

3.1 Wrinkling failure modes

The wrinkling of the face under compression is a typical and very important failure mode for sandwich panels with membrane-like faces (Fig. 2). As stated before, in a loaded sandwich panel, one

face is in tension while the other one is loaded by compressive stresses. A membrane under compression has, on its own, no stability, but it fails immediately through buckling. In a sandwich panel, the core provides a lateral support for the thin face and prevents the early buckling failure. The lateral support is activated when the face deforms in a wave-like pattern and induces stresses in the core material. The loss of the tensile strength of the core or the bond results in an immediate wrinkling failure of the face. Wrinkling is one of the most critical failure modes in a sandwich panel construction and it very often determines the ultimate limit state.



Figure 2. a) Wrinkling failure in a span and b) on an intermediate support.

3.2 Determination of wrinkling stress

The wrinkling stress is defined as the ultimate stress, a face can take in compression before it fails in buckling. The compression in the panel face is, in practice, induced by a bending moment that can, be caused by wind loads or temperature loads in multi span panels. Determination of the wrinkling stress of a sandwich panel generally requires full scale testing. The full scale test may be carried out by subjecting a simply supported beam to four line loads.

In a test setup according to figure 3 the ultimate bending moment (M_u) and the wrinkling stress (σ_w) for a lightly profiled panels are given by:

$$M_u = \frac{F_{Bu} L}{8} \quad \text{and} \quad \sigma_w = \frac{M_u}{e_c A_1} \quad (1), (2)$$

where

F_u	is ultimate load including self weight of panel and loading equipment
L	span of the test specimen
e_c	distance between the centroids of the faces
A_1	cross-section area of the face in compression

In order to be able to determine wrinkling stress after an artificial ageing, it is necessary to develop a small scale wrinkling test set-up which allows the determination of the wrinkling stress or more precisely the time dependent change of the wrinkling stress. The small sample can then fit into a climate chamber and tests on the aged samples can be performed.

3.3 Small-scale wrinkling test

The mechanical parameters necessary for the design may be obtained on the basis of the small scale testing. An exception is the wrinkling strength. For a durability research this poses the problem that it is not possible to determine the wrinkling strength after an artificial ageing. Therefore, a small scale test setup determining wrinkling strength has to be developed. When developing a small scale

wrinkling test for sandwich panels, it is the general idea to no longer induce compressive stresses in the face through a bending moment but to cut out a small panel area and expose it to a direct axial load in the direction of the plane. Baehre (1988) and Pfeiffer (2000) have previously tried to establish small scale wrinkling tests for the design of sandwich panels. However, it was not possible to determine the exact wrinkling capacity of a sandwich panel through small scale testing. The main problem in the earlier work was in finding a way to introduce the in-plane loads without damaging the thin face locally, a problem that does not occur in a full scale test. Special load application devices help to overcome the problem. During the test series it has been found that the full-scale bending test loads the sandwich panel twofold. In the upper face, the in-plane bending stress meets the deformation caused by the line loads, which evoke the actual bending moment and compressive stresses in the face. For a direct comparison between six point bending test and a small scale wrinkling test, this load combination must not be neglected. The results gathered in this project suggest that the research conducted by Baehre (1988) would have had a positive outcome if the local deformations were taken into consideration. With the results on hand, it was not possible to find a small scale test defining the wrinkling strength in the same way as a full scale test does.

3.4 New test set-up

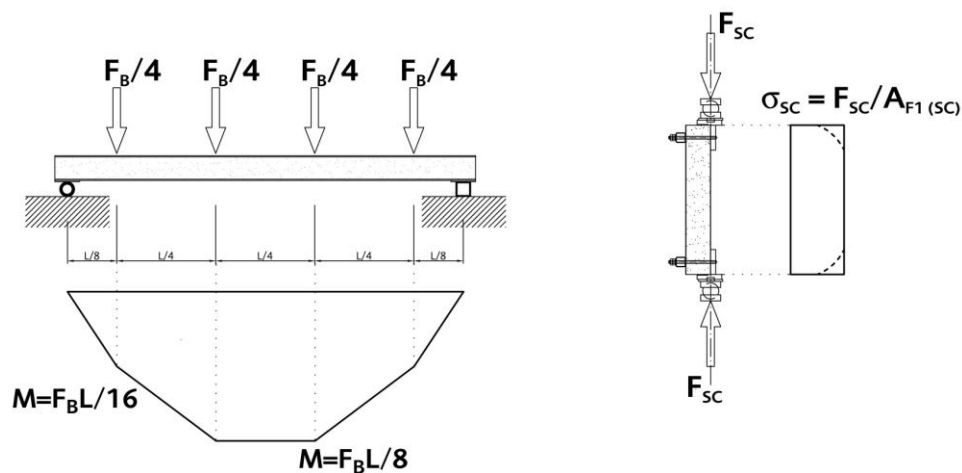


Figure 3. Arrangements of a full-scale and a small-scale wrinkling test with descriptions of the distribution of the bending moment and compressive stress.

The new test combines the two previously used test methods. Instead of causing compression in the upper face through a bending moment, the small scale test loads directly the face in a vertical, in-plane direction (Fig. 3). While the authors in their earlier work used a wooden T-shaped load application device, which was glued to a rectangular specimen with completely flat faces causing compression in one face, Baehre (1988) used a micro-profiled specimen with T-shaped load application devices made of steel. The load application device was not glued to the specimen but rather clipped onto it. In both cases the T-shaped device was chosen to gradually introduce the load to the specimen without causing local failures at the point of the loading (Fig. 4). Baehre failed to find a

small-scale test, giving similar results as obtained in a full-scale bending test. The reasons for this were the local deformations in the compressed face under the loading points in the full scale test. Such deformations weaken the observed wrinkling strength as they cause an additional local moment and additional stresses in the face. For a small scale test comparable to a full scale test this effect must be accounted for.

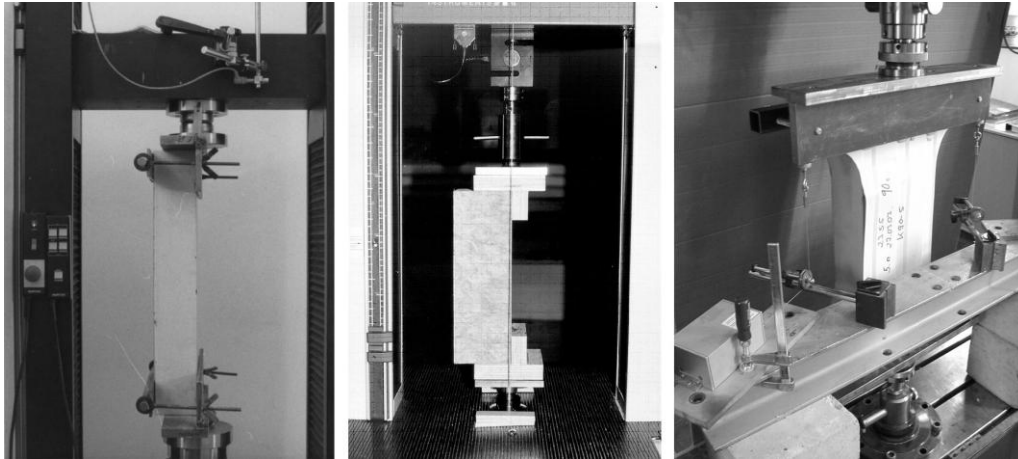


Figure 4. Test set-up of a small-scale wrinkling test from the left to right; Baehre (1988), Pfeiffer (2000) and Pfeiffer (2004).

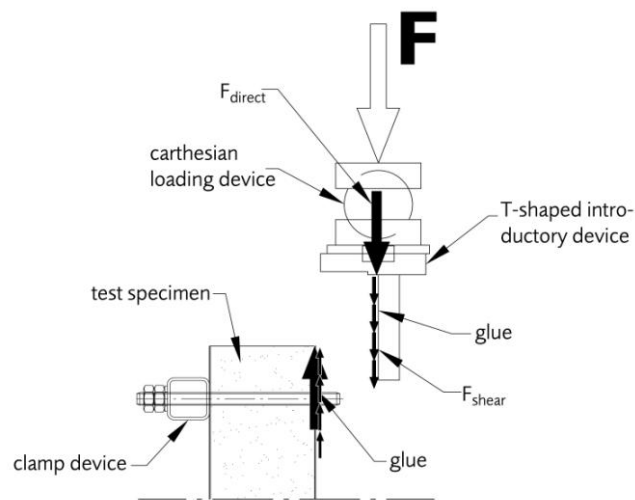


Figure 5. Introduction of the load in a small-scale wrinkling test. For illustration purposes, the specimen is separated from the load introduction device. The total load (F) is transferred to the specimen directly (F_{direct}) and through the shear force (F_{shear}).

For this work, a combination of the two previously described small-scale tests, determining the wrinkling stress, was chosen. The profiled specimen from Baehre was enlarged to a bone-shaped sample, again using T-shaped load application devices at both ends of the specimen. This time the application devices were both glued and clamped to the samples. Only the combination of gluing and

clamping together with the bone shape hinders the specimen from failing early through local crushing. Gluing the load application device to the samples allows the load to be introduced to the panel faces over a larger surface area, reducing concentrated load effects. The load is introduced through a shear force in the glue area and directly to the top and bottom ends, where the specimen touches the T-shaped device (Fig 5).

To study the effect of the local deformation at the load introduction areas in the full scale test, samples with and without local deformations were studied. A three step approach was taken. First, samples with completely undisturbed faces were tested, giving the maximum wrinkling stress that can be obtained. In a second step, the faces were dented prior to executing the small scale test. The depth of the imprinted deformations was of the same dimensions as observed in the full scale test. In a third step, the effect was simulated through a bi-axial loading in the small scale test. An additional load device was clamped to the specimen loading it in a perpendicular direction. All obtained results were compared to the results of the full scale bending test. The last procedure resulted in the most accurate results.

3.5 Test set-up based on rectangular specimen

Preparing of the bone-shaped specimens requires careful machining of the two metal sheets and the core. To simplify the preparation work, a test set-up has been developed, which base on a rectangular specimen. To avoid the failure at the end and to create a wrinkling failure in the mid-part of the specimen, the specimen is loaded by an additional transversal load (Fig. 6).

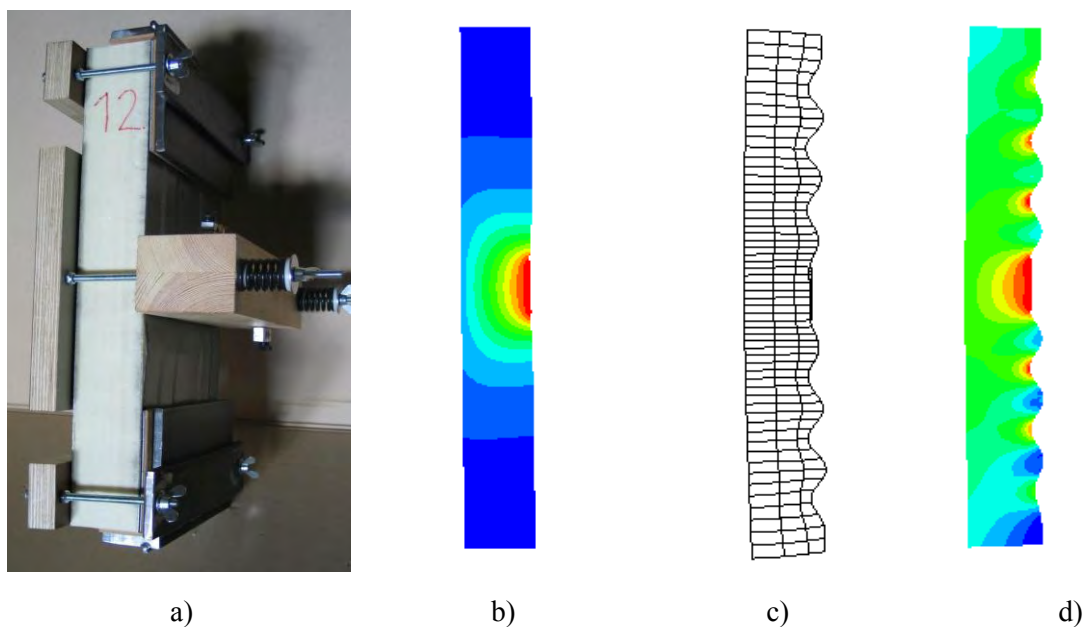


Figure 6. a) Rectangular small-scale test specimen, b) initial displacement caused by the transversal load (initial deformation equal to the face thickness, $w_0 \cong t_F$), c) displaced mesh and d) displacement caused by the transversal and axial load ($w_u \cong 3 t_F$).

Transversal load causes an imperfection in the face and compressive stresses in the core layer. The level of the transversal load has to be high enough to cause an initial imperfection to the wrinkling failure and on the other hand, lower than the elastic limit of the core layer (Fig. 7). Experiments on polyurethane-foam and mineral wool cored specimens have shown the test set-up to give acceptable modes of wrinkling failures.

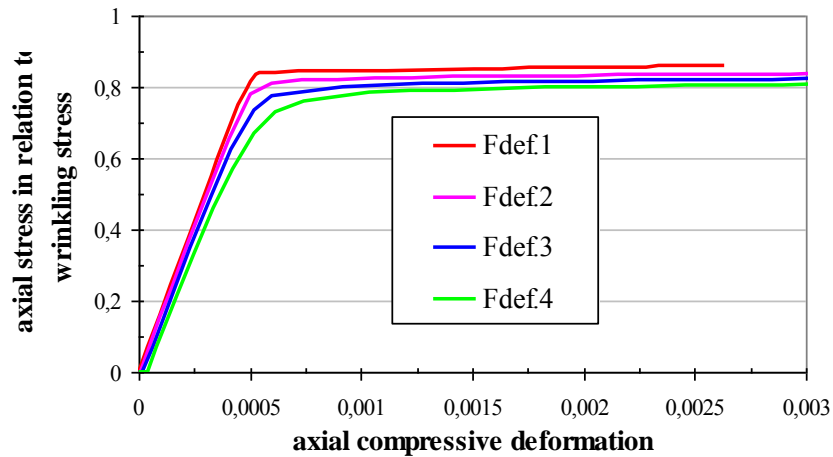


Figure 7. Influence of the transversal load on the stress-deformation behaviour of the face in the test described in Fig. 6. Transversal loads $F_{def,i}$ cause the transverse stress of 83, 63, 42 and 21 kN/m² in the core. The axial stress of the face is compared to an analytically determined ideal wrinkling stress of 125 N/mm² in the case.

Small-scale specimens will be exposed to an accelerated influence of the environmental actions. Because of the small size of the specimen, it is possible to create a large quantity of reliable information about the changes of the wrinkling stress in function of time and environmental loading history. The data will make the basis to the development of the design models in order to take into account the possible deterioration of the strength already in the design phase.

3.6 Comparing small-scale and full-scale tests

In order to calibrate the test setup, a test series, comparing the large-scale and small-scale test arrangements of the wrinkling stress was undertaken. All specimens in this series were taken from the same production batch. The full-scale panels were first tested as simply supported beams as described previously. The test panels had a PUR core between the two steel faces. The wrinkling failure obtained in the full scale tests resulted in an average wrinkling stress of 180.94 N/mm² (individual test results between min. 180.75 N/mm² and max. 181.27 N/mm²). The wrinkling failure, obtained from the small scale test without the additional effect of the transversal load, averaged to 228.73 N/mm² (individual test results between min. 223.06 N/mm² and max. 234.76 N/mm²).

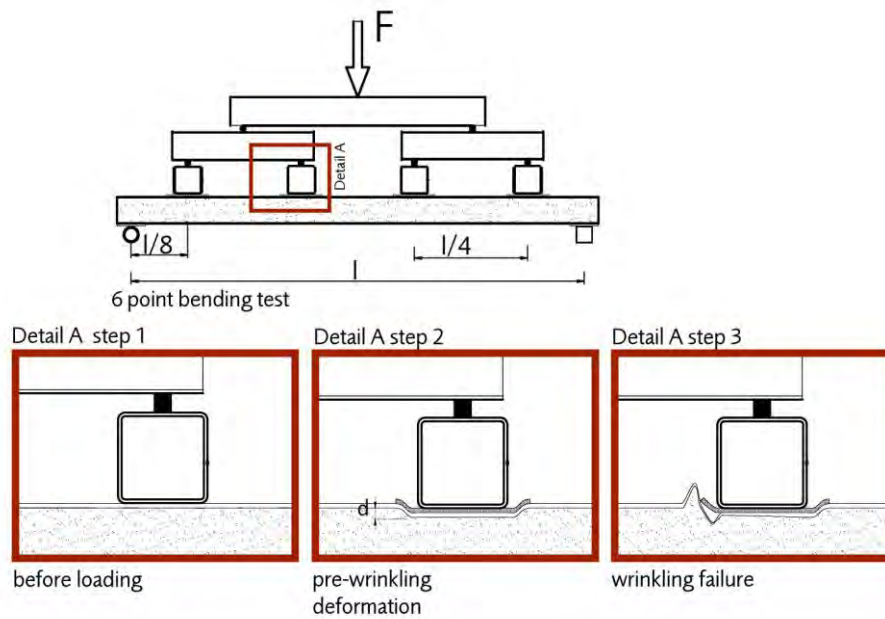


Figure 8. Local deformation in the loading point causing an early failure in the six point bending test. The discontinuity (d) occurs under all loading points but interacts with maximum bending moment at the indicated point.

Comparing the results given by the two methods, a difference of 26.4 % can be found. This difference is not acceptable if the determination of the accurate wrinkling stress is required. The reason for the observed difference lies in the test setup of the full scale bending test. In a six point bending test the load is transferred to the panel in four line loads (Fig. 8). At the point of the load introduction, this results in deformations of the face causing a failure at the inner point of the loading beam, where maximum local deformations and the maximum bending moment interact. In order to achieve the same results from the small scale testing as determined through full scale testing, this deformation effect needs to be taken into account. An additional loading device generating a transverse load, was introduced in the test. This additional device loads the panel perpendicular to the faces, causing the same local deformation as obtained in the full scale test. The load is applied through two steel profiles, having the same dimensions as the ones used in the full scale test. The loading is controlled with the help of two screws and measured in a load cell. At an average of 178.79 N/mm^2 (individual test results between min. 177.07 N/mm^2 and max. 180.50 N/mm^2) the results obtained from the setup show good correlation with the results of the full scale bending test. When comparing the average results, 98.8 % of the strength determined in the full scale bending tests could be reached.

The results indicate clearly that it is possible to use the small scale testing to determine the accurate wrinkling strength of a sandwich panel. It is, however, necessary to simulate the full-scale test accurately and to take into account even the small details, like the local deformations at the load introduction points.

When lacking knowledge of the maximum load obtained in the full scale test (F_{max}), which is the case when no full scale test has been carried out on a particular panel, it is necessary to gradually increase

the deformation load relative to the load parallel to the face. The load needed on the deformation device can be calculated on the basis that the stress parallel to the face shall be equal in the both tests. This means, that a certain load in the small scale test, corresponds to a certain load in the full scale test, both causing the same stresses parallel to the surface. At the same time this load determines the load on the additional load device and can be calculated as described in the following:

The membrane stress in the flat face in the six point bending test can be written by

$$\sigma_{f6P} = \frac{F_{6P} L}{8 e_C A_{f16P}} \quad (3)$$

where σ_{f6P} is the stress in face in 6 point bending test
 F_{6P} total load on panel in 6 point bending test
 A_{f16P} : cross sectional area of the face in compression in 6 point bending test

The corresponding stress in the small scale test is given by

$$\sigma_{fsc} = \frac{F_{sc}}{A_{f1sc}} \quad (4)$$

where σ_{fsc} is the stress in the face in the small scale wrinkling test
 F_{sc} total load parallel to the face in the small scale wrinkling test
 A_{f1sc} cross sectional area of the compressed face in a small-scale test

A simulation of the full scale test through the small scale test requires an equal stress parallel to the face (wrinkling stress). Equating the equation 3 and 4 gives the load F_{6P}

$$F_{6P} = \frac{8 F_{sc} e_C b_{6P}}{L b_{sc}} \quad \text{which can also be written as} \quad \frac{F_{6P}}{4} = \frac{2 F_{sc} e_C b_{6P}}{L b_{sc}} \quad (5)$$

in which t_{fl} net thickness of the face
 b_{6P} width of the panel in the 6 point bending test
 b_{sc} width of the sample in the small-scale wrinkling test

Local stresses in perpendicular direction to the face in the load introduction point are

$$\sigma_{def.6P} = \frac{F_{6P}}{4 b_{6P} B} \quad \text{full-scale test and} \quad (6)$$

$$\sigma_{def.SC} = \frac{F_{def}}{b_{sc} B} \quad \text{small-scale test} \quad (7)$$

where B is the width of load application device in the set-ups

For comparison of the two tests, the local transverse stresses need to be equal, which results in

$$F_{def} = \frac{F_{6P} b_{SC}}{4b_{6P}} \quad (8)$$

Combining the equations 8 and 5 leads to

$$F_{def} = \frac{2F_{SC} e_C}{L} \frac{b_{6P} b_{SC}}{b_{SC} b_{6P}} = \frac{2F_{SC} e_C}{L} \quad (9)$$

The load in the additional deformation device can now be calculated, depending on the axial loading of the sample, the distance between the centroids of the two panel faces, and the span length of the static system in the six point bending test.

4. Conclusions

The results presented in the paper indicate that the small-scale wrinkling test can be used in the evaluation of the wrinkling stress. The test requires extensive preparation work such as bone shape or rectangular cutting and gluing and fixing of the load application devices. Laboratories dealing with sandwich panel technology on a regular base can adopt the test with some additional work. For further work on the durability related degradation of the wrinkling stress, it is sufficient to consider only the durability related changes and thus the relative values. In future research work the test arrangements without the additional deformation device will be studied. Also a simplified rectangular wrinkling test set-up will be developed further.

The shear and compression strength of the core is determined in most cases on the basis of the small-scale tests. Thus, the durability of the shear and compressive strength can be studied by exposing the specimens to accelerated deterioration processes in a climate chamber. These studies will contribute further information to the evaluation of the durability of the structural sandwich panels.

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