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Deformation Analysis of Sandwich Surfaces Prior to Buckling Failure Employing a 3-d Scanning System and Open Source Image Processing Software*

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Abstract: We apply a mobile 3-d scanning system to achieve an accurate deformation analysis of sandwich elements. This strategy offers the detection of geometrical changes in the sandwich face under increased loading. The results are assessed, both in quality and quantity. It is the aim of the research to assure theoretical modeling of wrinkling (short buckling) failure of sandwich structures. This paper discusses particularly the background of the scanning request as well as implementation aspects concerning the open source public domain image processing software package ImageJ and the results obtained.

Zusammenfassung: Analyse der Verformung von Sandwich-Oberflächen vor dem Knitterversagen mittels Einsatz von 3D-Scanner und Open Source Bildverarbeitungssoftware. Mit einem mobilen 3D-Scansystem werden Deformationsmessungen an Sandwichelementen durchgeführt. Durch die zügige und flächenhafte Erfassung geometrischer Oberflächenveränderungen werden qualitative und quantitative Aussagen zum Beulverhalten der Sandwichdeckschicht unter wachsender Belastung gewonnen. Ziel ist die Absicherung der theoretischen Modellbildung des Bauteilverhaltens. In diesem Beitrag werden neben dem Hintergrund der Messaufgabe auch die Implementierung unter dem Open Source Public Domain Bildverarbeitungspaket ImageJ und die erzielten Ergebnisse diskutiert.

1 Introduction

Since its foundation in 1998 the i3mainz – Institut für Raumbezogene Informations- und Messtechnik (Institute for Spatial Information and Surveying Technology) – has 3-d scanning and 3-d visualisation as one of its main focuses. Among other things a test range for medium range terrestrial laser scanners has been set up, BÖHLER & MARBS (2002). The federal state of Rhineland-Palatinate has founded a centre of competence for *Spatial Information in Humanities*, making latest mobile 3D scanning systems available. With a Leica Cyrax 2500, a Mensi SOISIC, a 3dscanners Modelmaker X70 mounted on Faro's seven-axis portable measurement arm and a GOM ATOS II application oriented research and development on objects varying in size between ten centimetres and several hundred meters is undertaken, BÖHLER et al. (2004). In spring 2006 the construction of a long awaited new building, including state-of-the-art geodetic laboratories and other supporting facilities starts, in direct neighbourhood to Mainz university. The scientific areas are flexibly designed to meet i3mainz's demanding metrology requirements well into the upcoming century.

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2 Sandwich elements in construction

Sandwich elements have become increasingly popular in the construction sector over the last decade. In particular when applied as a building envelope combining high thermal insulation values as well as great stability such panels are a good alternative to conventional construction. The biggest advantage of sandwich constructions is the fast erection time and the high degree of in shop pre fabrication, which minimizes building time and optimizes building quality.

2.1 *Structural performance and composition of sandwich elements*

Sandwich elements are load bearing construction members. They transfer loads such as wind and snow loads to the supporting frame. Because of their unique cross section, consisting of a rigid core between two thin metallic faces, sandwich panels show different failure modes than conventional building materials. One of these unique failure modes is a short buckling failure of the compressed face under moment induced stresses, the so called wrinkling failure. While the shear force is taken by the core, a pair of forces originating from the bending moment stresses the panel's top and bottom face. Generally these faces are very thin in comparison with the core and have no flexural stiffness on their own. Therefore these facings must be supported by the core, hindering them from early buckling. The mechanical properties of the core are therefore of great importance for the load bearing capacity of the whole structure.

2.2 *Determination of ideal wrinkling strength*

Theories determining the wrinkling strength of a sandwich structures are in principle available, LINKE (1978), PLANTEMA (1966). Such theoretical approaches however deliver unsatisfactory results when comparing to experimentally determined values. In principle these theories are based on an ideal wrinkling strength, seeing the wrinkling strength as an eigenvalue problem of the compressed face failing through buckling. Following PLANTEMA (1966) this can be described by the formula:

$$\sigma_{wi} = 0.851 \cdot \sqrt[3]{E_f \cdot E_c \cdot G_c}$$

where

σ_{wi} ideal wrinkling strength
E_f Young's modulus of the face
E_c Young's modulus of the core (av. of compression and tension)
G_c shear modulus of the core

2.3 *Bedding stresses of the core*

Prior to wrinkling failure the compressed face shows undulated deformations. These deformations activate the supporting capabilities of the core. Both, LINKE (1978) and PLANTEMA (1966) assume this deformation to follow a sinusoidal shape. The resulting stresses in the boundary layer between face and core are illustrated in Fig. 1.

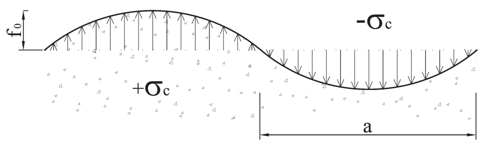

Fig. 1: Supporting stresses at the boundary layer between face and core.

Tensile and compressive forces are generated. If the bonding strength between face and core or the tensile or compressive strength of the core is insufficient and unable to support the face layer, the sandwich fails in buckling before the ideal wrinkling strength is reached. The bedding stress on the core can be determined mathematically, LINKE (1978). The absolute value of the maximum bedding stress is determined through:

$$\max \sigma_c = \frac{\pi}{a} \cdot \sqrt{E_c \cdot G_c} \cdot f_0 \cdot t \cdot \frac{\sigma_x(i)}{\sigma_{wi} - \sigma_x(i)}$$

where

σ_c present bedding stress in core
a length of sinusoidal half wave

f_0 amplitude of sinusoidal half wave
t thickness of compressed face
$\sigma_x(i)$ present normal stress in face
σ_{wi} ideal wrinkling strength

The bedding stress in the core is therefore not only dependent from the mechanical properties of the core and the normal stresses in the face but also from the amplitude and the wave length of the sinusoidal half wave. The material factors can be determined accurately on the base of small scale testing (prEN 14 509). The properties of the sinusoidal pre wrinkling deformation are, up to now, however only based on assumptions. LINKE (1978) shows that the length of the sinusoidal half wave is determined through:

$$a = \pi \cdot \sqrt[3]{\frac{2 \cdot D}{\sqrt{E_c \cdot G_c}}}$$

where
D flexural stiffness of face

For the amplitude of the half wave LINKE (1978) refers to PLANTEMA (1966) and assumes

$$f_0 = \frac{a}{500}.$$

When determining the bedding stress of the core, the influence of the amplitude has a linear character. The divisor of 500 is however only estimated and based on guessing. No experimental acknowledgement has been undertaken, as accurate surveying methods were lacking. When conducting experiments determining the wrinkling strength of a sandwich structure such deformations are hardly visible to the naked eye.

3 Experimental realization

In order to determine the bedding stresses on the sandwich core it is necessary to accurately observe the deformation of the panel surface during a testing, see Fig. 2. Wavelength and amplitude as well as wave form need to be determined precisely to provide an insight into the material behaviour. In this research sandwich panels with a polystyrene core between two faces of steel sheet were investigated. The exact material properties of the face and core were determined experimentally, following the procedures as described in prEN 14 509. Applying the above presented theory, the wavelength was expected to be 78.8 mm while the expected amplitude was 0.16 mm. Two test setups were tested. One investigated panels in a six point bending test, see Fig. 2, as described

Fig. 2: Setup for six point bending test (left); sandwich after wrinkling failure (right).

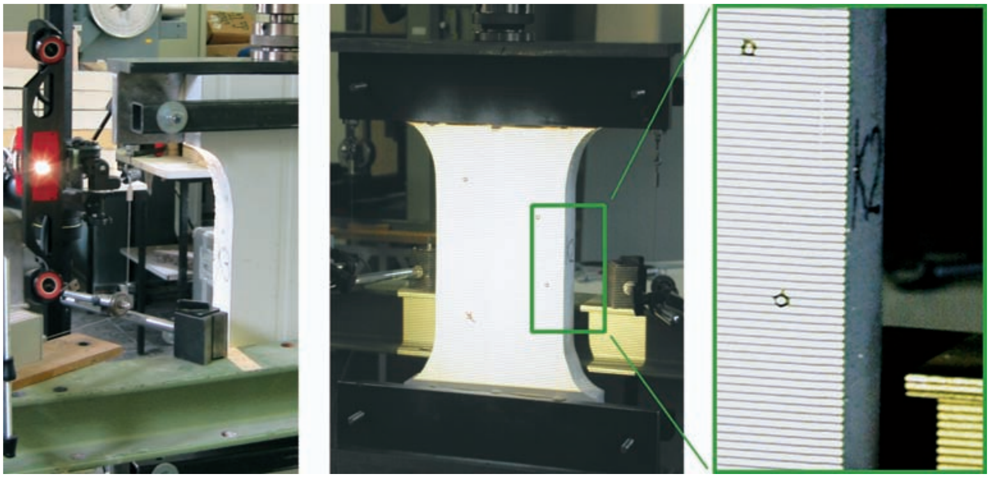

Fig. 3: Setup with band projection scanner GOM ATOS II and the small scale test setup: Fringe projection scanner GOM ATOS II with two digital cameras on a fixed base, in the center position the fringe projector is actually working (left), sandwich element and projected fringes (middle and right).

in prEN 14 509. The other explored a newly developed small scale test on wrinkling strength, see Fig. 3. In both setups the area with the largest compressive stress in the face were studied.

The use of three different testing machineries together with both horizontal and vertical orientations of the test specimens and varying sizes of the measuring fields calls for the application of mobile 3D coordinate measurement techniques. The photogrammetric fringe projection system GOM ATOS II was chosen as 3-d scanner because it provides the necessary flexibility in instrumental setup together with a sufficient geometrical resolution well below the tenth of one millimetre. The system requires a recording time between 15 and 20 seconds, which was acceptable to the test setup. A testing scheme consisting of 10 to 12 load increments can be secluded in about 15 to 20 minutes, including scan sequences for all load cases. The absolute displacement of the panel in vertical direction during the test (bending deformation) is not of interest for this research. The frame of reference is therefore defined with the help of retro reflecting target points sticking directly on the panel surface as noticeable in both Figs. 2 and 3. The analyzing software then converts the true movement of the object into a calculative displacement of the sensor. This was in advance simulated under controlled circumstances using a levelling disc, WEIDES (2003).

The scanned 3D points were converted into triangular meshes and translated into the 2.5 D grid pattern of a digital image with 32 bits per pixel. The TIFF file format offers a standardized way to handle such kind of surface data. To visualize the precise deformation of the sandwich face layer different load increments are subtracted from one another. The remaining differences between load increments are then subjected to frequency analysis. Basically the remaining deformations can be segmented into a low frequency fraction, representing the global bending deformation of the whole panel and the sought-after high frequency fraction caused by the pre wrinkling deformation of the face, see Fig. 4.

4 Implementation aspects

As different sandwich panels show varying profiling of the deck layers, depending on producer and mode of application, some

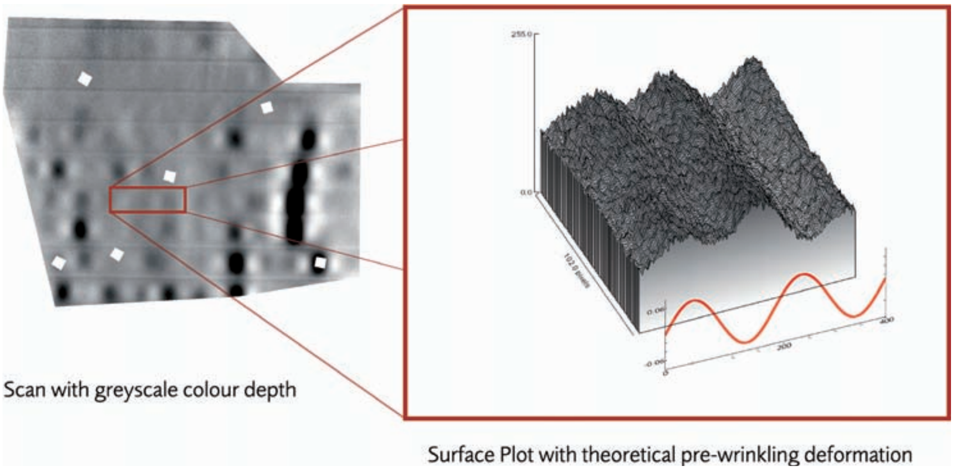

Fig. 4: Pre wrinkling deformation after deviation of load increments with grey scale indicating level of deformation (left); three dimensional surface plat with theoretical sinusoidal deformation (right).

flexibility in varying the image processing flow was necessary. For this purpose the open source public domain image processing software ImageJ (RASBAND 1997–2006) was adopted for the project, cf. Fig. 5. ImageJ offers the following advantages: minor changes of image processing can be done directly and parallel based on the gathered surface data; both, users and scan service providers can use a shared evaluation programme due to the public domain status of the software; the programming language Java allows application on the Linux based PC of the GOM scanning system as well as on the Microsoft Windows based platform of the user; interactive macro recording offers directly editable Java source code; extraction of surface profiles and export to a spread sheet analyzing programme is fairly easy using simply drag'n drop. Further analysis such as discrete Fourier transformation can then be undertaken without problem.

We found it helpful to integrate even the importer tool for the 2.5-d point clouds directly under ImageJ. The open source ImageJ plugin „XYZ2DEM Importer" imports X,Y,Z coordinates of (usually irregularly distributed) points from the first 3 columns of a plain text file and interpolates a Digital Elevation Model (DEM) image using a Delaunay triangulation, SCHLÜTER & JOE (2006). „XYZ2DEM Importer" is available for free download from NIH's (U.S. National Institutes of Health) website.

Fig. 5 illustrates the application of ImageJ using a 32-bit depth image. Fig. 5 exemplarily illustrates the manual processing of 32 bit depth images with ImageJ. On the one hand the user has direct access to the calibrated metric surface data with standard methods (like "depth value under crosshair: −3.283 mm"; the marked profile indicates further options like "histogram along profile" etc.). On the other hand an exhaustive and open image processing environment with excellent suitability for depth image processing is available in the background. This offers interesting perspectives for scientific interdisciplinary co-operations, since photogrammetric experts and collaborating scientists of different expertise might use ImageJ as a common platform for further developments without substantial initial investments.

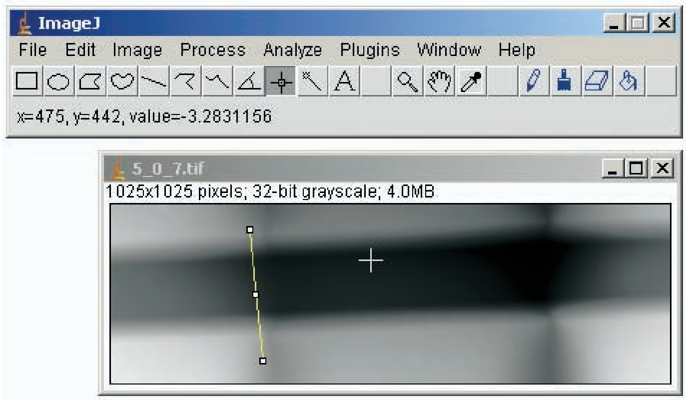

Fig. 5: Processing of a 32-bit depth image with ImageJ (screenshot).

5 Conclusions

It was the aim of this study to investigate the pre wrinkling deformation of a sandwich deck layer under compression with respect to the investigation of durability assessment of sandwich panel construction, PFEIFFER (2005). With the help of 3-d scanning sandwich panels in bending tests were examined.

With the help of 3-d scanning it became possible for the first time to visualize the buckling deformation of the compressed face. Good correlation between the theoretically predicted wavelength and the experimental results was found. In principle this is also true for the amplitude of the wave shaped deformation. The results here are however not as homogeneous. Small local disturbances, which are not taken into consideration in the theoretical model, can lead to great local deformations under loading. For further investigations as well as for modelling with the help of finite element analysis the obtained results form a good basis. In particular for the determination of the influence of cross panel tensile strength on wrinkling strength, the obtained results are adopted for a new model, PFEIFFER (2005). This model now allows for a new, quantity driven, evaluation of long term deterioration effects for sandwich structures.

Last but not least the open source image processing software ImageJ has proved it's worth for scientific interdisciplinary co-operation. Using ImageJ, photogrammetric experts and collaborating scientists of different expertise can share a common software platform without substantial initial investments.

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