

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Laser-welded corrugated core steel sandwich panels for bridge application

PETER NILSSON

Department of Architecture and Civil Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Thesis for the degree of Licentiate of Engineering
Department of Architecture and Civil Engineering
Division of Structural Engineering
Steel and Timber Structures
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000
www.chalmers.se

Cover:

Upper left: Corrugated core steel sandwich panel, from Paper I. Upper right: Corrugated core sandwich cell subjected to global sectional force and moment, created by the author. Bottom left: Image of a core-to-face joint, photo by the author. Bottom right: Laser-welding image, photo: Kleven Verft AS.

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To Lovisa, Matilda and Olle

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ABSTRACT

The design of steel bridge decks has remained unchanged since the introduction of orthotropic decks. Orthotropic decks are expensive to produce, mainly due to high labor-costs. Furthermore, several joints (within the deck and between the deck and the surrounding structure) are highly fatigue sensitive, and the deck has a low stiffness in the transverse direction (i.e. perpendicular to the longitudinal stiffeners). This has in many cases led to premature deterioration and high maintenance costs. This thesis has a focus on laser-welded corrugated core steel sandwich bridge decks that have an increased stiffness-to-weight ratio and a more industrialized production with less complex detailing compared to conventional orthotropic steel decks. These enhancements lead to a more attractive solution with respect to economic and environmental sustainability.

Structural analysis of a three-dimensional corrugated core sandwich panel using numerical methods is computationally heavy. In particular, the structural behavior of such panel in the transverse direction is rather complex. For that reason, this thesis is aimed at developing methods for simplified analysis incorporating homogenized beam and plate theories. Focus is put on predicting the stiffness and load effects in the direction transverse to the corrugation. A second aim of this thesis is to investigate the impact of variation of the production-dependent geometric parameters of the core-to-face joints of corrugated core steel sandwich panels on fatigue-relevant stresses in the vicinity of the laser stake welds.

In order to utilize a simplified approach for static analysis of a corrugated core steel sandwich panel, a new analytical formulation for the transverse shear stiffness in the weak direction of the panel is presented in this thesis. To ensure that this stiffness property yields accurate predictions, the rotational rigidity of the weld region is simulated by a rotational spring. The magnitude of this spring is determined by a closed-form solution based on numerical and regression analyses. Both the transverse shear stiffness and the rotational spring is verified by numerical analyses and experiments. Furthermore, the impact of the variation of the production-dependent parameters is studied in this thesis by an extensive parametric study incorporating two-dimensional continuum numerical models. Numerical results are presented and discussed in detail. As an example, the parametric study shows that a misalignment between the weld-line and core direction can lead to a large increase of the fatigue-relevant stresses.

Keywords: laser-welding, sandwich panel, shear stiffness, corrugated core, joint geometry

PREFACE

The work presented in this thesis was performed at Chalmers University of Technology between January 2015 and November 2017 as a collaboration between the department of Structural Engineering at Chalmers and the company WSP. This research was founded by the Swedish Transportation Administration, the Swedish research agency Vinnova and the Norwegian Public Roads Administration as a part of the project “Costal highway route E39”.

First and foremost, I would like to direct my sincerest gratitude to my supervisor Associate Professor Mohammad Al-Emrani for his support and guidance during this period. My co-supervisor Rasoul Atashipour, PhD, his support in this project is greatly appreciated. Roland Olsson, department manager at WSP Bridge and Hydraulic design in Gothenburg; I thank you and the company, for supporting me in this work.

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Gothenburg, 2017

Peter Nilsson

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

PAPER I

P. Nilsson, M. Al-Emrani and S.R. Atashipour, *Transverse shear stiffness of corrugated core steel sandwich panels with dual weld lines*, Thin-Walled Structures, Vol 117, pp 98-112, August 2017.

PAPER II

P. Nilsson, M. Al-Emrani and S.R. Atashipour, *A numerical approach to the rotational stiffness of stake welds*. Proceedings of EUROSTEEL 2017, pp 489–498, Copenhagen, Denmark

PAPER III

P. Nilsson, J. Hedegård, M. Al-Emrani and S.R. Atashipour. *The impact of production-dependent geometric properties on fatigue-relevant stresses in laser-welded corrugated core steel sandwich panels*. To be submitted.

AUTHOR'S CONTRIBUTIONS TO JOINTLY PUBLISHED PAPERS

The contribution of the author of this licentiate thesis to the appended papers is described here.

- I. Responsible for the preparation of the manuscript for the paper. The author performed the literature review, defined the setup for the analytical solution, executed the derivation and verification and was responsible for the conclusions.
- II. Responsible for the preparation of the manuscript for the paper. The author performed the literature review, defined the setup for the numerical solution, executed the parametric study, executed the regression analyzes and was responsible for the conclusions.
- III. Responsible for the preparation of the manuscript for the paper, apart from Section 2. The author performed the literature review, defined the setup for parametric study, executed the parametric study and was responsible for the conclusions. Furthermore, the author was responsible for all preparations of specimens before measurements and executed all measurements except for the weld widths and plate gaps of Beam 1.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Conference Papers

P. Nilsson and M. Al-Emrani, *Industrialized light-weight steel bridge concept using corrugated core steel sandwich plates*, IABSE Congress Stockholm 2016; Challenges in Design and Construction of an Innovative and Sustainable Built Environment, pp 543 - 551, Stockholm, Sweden.

Reports

P. Nilsson, *Steel-sandwich elements in bridge applications*, Chalmers University of Technology, Report 2015:11, 2015.

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1 INTRODUCTION

1.1 BACKGROUND

Bridges are structures affecting the social, economic and environmental aspects of sustainability. Structural solutions for bridges that are sustainable are sought for by governmental transport administrations world-wide. Within the research project Pantura [1], European bridge owners responded to a questionnaire regarding bridge demographics, maintenance and costs, etc. Statistical analysis of the responses showed that about 45% of all rehabilitation activities on bridges are devoted to repair and replacement of steel decks and concrete decks in composite bridges; see Pantura D5.3 [2]. Thus, bridge decks are vulnerable and highly relevant with respect to the life-cycle perspective of a bridge.

The deck of a bridge has multiple functions in terms of load bearing. Figure 1 illustrates three types of load-bearing functions of a bridge deck. It shall withstand the locally applied load from a wheel pressure (see Figure 1a). Moreover, it shall effectively distribute the load to the underlying supporting structure, i.e. main girder system or abutment (see Figure 1b). Furthermore, it is most often also utilized in composite action as a flange in the main load-carrying structure (see Figure 1c). Thus, versatile structural demands are placed on bridge decks; to carry load locally, to distribute them effectively through plate action and to withstand high membrane forces from global action. Local deformations, as shown in Figure 1a, need to be restricted not only with respect to the structural performance, but also because they can lead to pavement deterioration causing extensive maintenance costs and traffic disturbance. The choice of bridge deck type for a new structure or deck replacement in an existing bridge, is based on different owner priorities. During the above mentioned research project Pantura [1], four European bridge owners listed their order of priority and the results showed that costs and construction time were rated high.

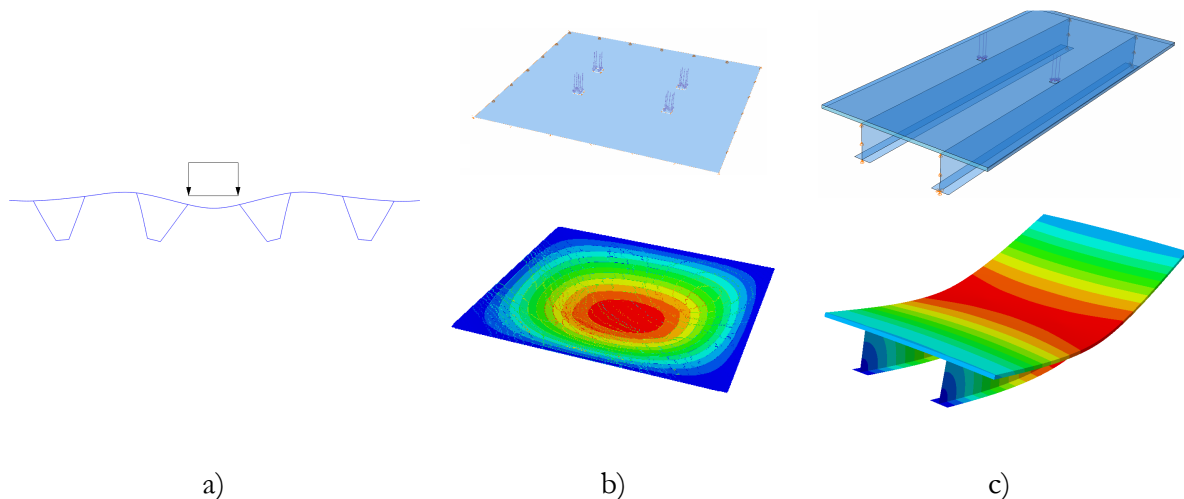


Figure 1. Bridge deck actions; a) local action due to wheel pressure for a conventional orthotropic steel deck, b) plate action for load distribution, c) flange action for global stiffness and strength.

Due to the fact that bridge decks are important structural parts for the whole bridge structure and important for the total bridge economy, they have been constant subjects of research and innovation. Today concrete bridge decks are by far the most common type of solution in Sweden. Their main benefits are that the knowledge of their design, production

and long-term performance is well documented and known within the industry. However, they are mass-intensive and have a large CO₂-footprint. Aluminum decks have been used to a relatively wide extent in bridge rehabilitation. Among others, Arrien et al. [3] reported that aluminum bridge decks are light-weight, weighing only one tenth of a concrete bridge deck and they are competitive by an ease of on-site assembly. Nevertheless, the drawbacks are low stiffness, non-composite action with the underlying main structure, extensive maintenance in the joint region with pavement and a high initial cost. For these reasons, aluminum bridge decks are not used in Sweden as often today as for twenty years ago. Fiber Reinforced Polymer (FRP) bridge decks have been developed and used for the last decade, see Mara et al. [4]. They are very light-weight and have a high fatigue and corrosion resistance. Nevertheless, the initial costs are high and their long-time performance has not yet been fully investigated. Sandwich Plate System (SPS) bridge decks, developed by Intelligent Engineering [5], benefit from a high stiffness and low weight, and have been used in several countries such as US, China, Germany and Canada [5]. The deck basically consists of two steel face sheets interconnected with an elastomer core. Harris [6] stated that the lack of design-models is the main obstacle for a wider implementation of SPS bridge decks. However, there is a lack of information in the literature regarding cost-efficiency and long-term performance of the concept as well.

Conventional orthotropic steel decks (see Figure 2) possess a high stiffness-to-weight ratio in their longitudinal direction and are thereby an attractive solution for many bridge applications. However, they are labor-intensive to produce and suffer from premature deterioration that leads to high investment and maintenance costs, respectively. The premature deterioration originates from a low local stiffness in the direction orthogonal to the stiffeners that causes large deformations and thereby occurrence of cracks in the pavement. Furthermore, conventional orthotropic decks are fatigue sensitive. Due to the high investment and maintenance costs is a conventional orthotropic deck in general only considered as an economically feasible option for cases where the structural weight is of the outermost importance; see e.g. Bright and Smith [7] or Kolstein [8]. Bright and Smith [7] stated that an orthotropic steel deck is about four times as expensive as a concrete deck and the fabrication costs of the steel deck often exceed the material costs [7].

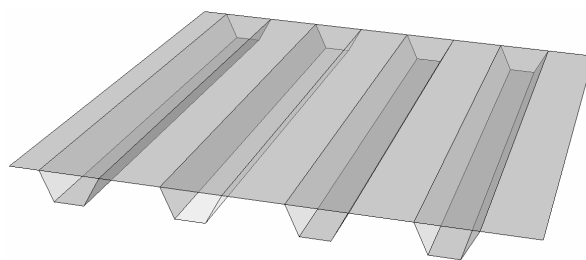


Figure 2. Conventional orthotropic steel bridge deck.

Laser-welded all-steel sandwich panels have been proposed for bridge deck applications by several researchers (see Bright and Smith [7], Caccese and Yourulmas [9], Klostermann [10] and Nilsson et al. [11]). A laser-welded corrugated core steel sandwich panel (CCSSP) is shown in Figure 3a. All-steel sandwich panels can be produced by two main laser-based welding processes. Either a pure laser process is adopted, or a hybrid-process involving conventional arc-welding. Figure 3b shows a robotic laser-welding equipment. The main property of the laser-based welding processes that enables the one-sided welding is the high energy density of the laser beam, making a deep penetration possible. Compared to

conventional steel bridge decks, CCSSPs are produced in a more industrial manner. Not only the production of the deck itself is fully automatized, but connections to the main load-carrying structure is more straight-forward when CCSSPs are used compared to the conventional solution. Conventional stiffened plates are connected to the web of transverse girders with a complex procedure involving curved welding paths that today most often is performed manually. The corresponding connection for a CCSSP can be a double-sided straight fillet-weld, see Figure 3c for a comparative illustration. Structurally, all-steel sandwich panels are weight-efficient compared to conventional stiffened plate solutions and material savings ranging from 10-50% (see e.g. Beneus and Koc [12], Kujala and Klanac [13], Roland and Reinert [14] and Kujala et al. [15]) is reported in the literature for both bridge and ship structures. These weight savings are not on the deck alone, but the weight decrease of the surrounding structure working in full composite action is also included. The structural efficiency of CCSSPs in comparison with conventional orthotropic decks stems from three key aspects: an increased bending stiffness in the longitudinal directions of the core due to a shift of the neutral axis, an increase of the bending stiffness in the perpendicular direction due to a sandwich effect also in that direction and an increased efficiency when the deck is utilized as a flange due to a less pronounced shear-lag effect, see Figure 3d-f.

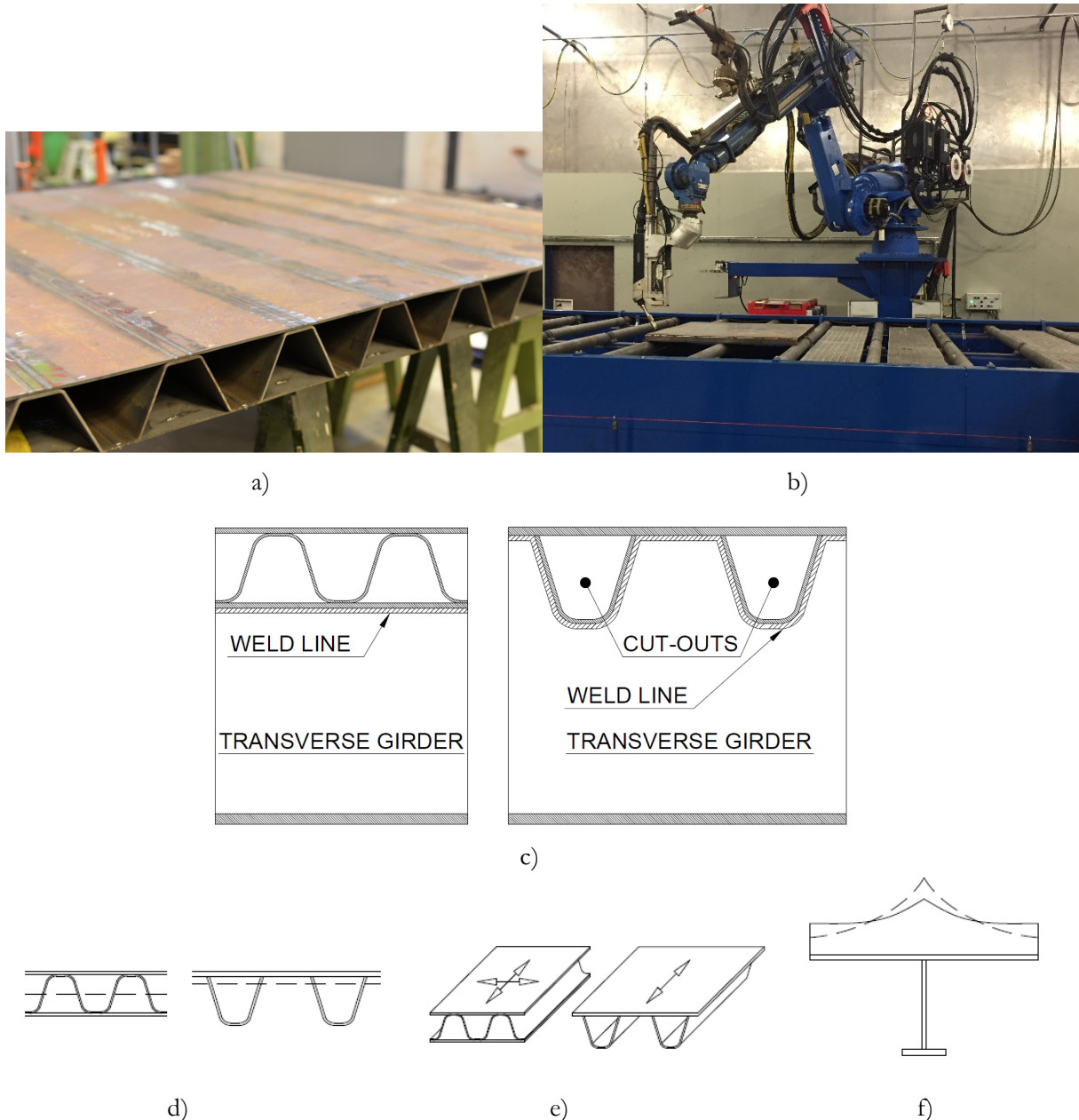


Figure 3. a) Laser-welded corrugated core steel sandwich panel, b) laser-welding equipment, photo: Kleven Verft AS, c) comparison of deck to transvers girder between all-steel sandwich panel (left) and conventional stiffened plate (right) [11] d) increased bending-stiffness in the main direction, e) increased 2-way load distribution f) shear-lag comparison (dashed = conventional, solid = sandwich panel).

The core of an all-steel sandwich panel may be produced with different shapes. A range of possibilities of core types are shown in Figure 4. All cross sectional shapes in Figure 4, except for E, can be produced by laser-welding (E in Figure 4 shows an extruded aluminum section). All the cross sections in Figure 4 are orthotropic and have approximately equal bending stiffness in the longitudinal and transversal direction. What separate the core geometries are their material consumption, shear stiffness in the direction orthogonal to the core (i.e. the weak direction) and production aspects. The inclination of the core leg for the CCSSP (A in Figure 4), gives it an increased shear stiffness in the weak direction compared to those with straight cores, for instance B (web-core) and G (C-core) of Figure 4 (see e.g. Lok and Cheng [16]). Thus, the inclination of the core leg yields an enhanced two-way load-carrying behaviour, i.e. plate action, beneficial for several bridge applications. Furthermore, enhanced plate action increases the spread of a concentrated load (e.g. wheel pressure).

However in general, the CCSSP consumes more material than the web-core and C-core sandwich panel. Thus, the most material effective type of core configuration depends on the type of loads and boundary conditions (BCs). For a bridge deck supported by longitudinal and transversal girders, the pronounced plate action of the corrugated core is beneficial.

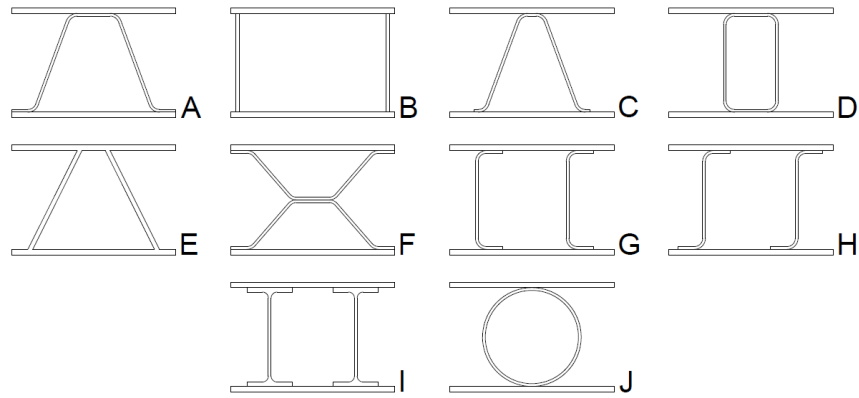


Figure 4. 10 possible structural core sandwich panel geometries [11].

For applications where conventional orthotropic bridge decks are used today, an all-steel sandwich panel bridge deck can be used with the benefits discussed above. Movable bridges (see Figure 5) and a deck-plate in a box-girder of a cable-supported bridge, are two examples of that. Furthermore, Dackman and Ek [17] showed that for medium-span bridges which in Sweden are commonly made of steel with concrete decks in composite action, a CCSSP bridge deck could instead be used resulting in a bridge that could be launched in one piece. This yields a promising bridge concept, especially in urban areas. Ungermann and Russe [18] proposed usage of a sandwich panel bridge (without girders) for road traffic, simply supported on two edges. This is a concept where complete prefabrication of the bridge superstructure is possible and the light weight of the bridge yield an ease of the on-site construction. The main limiting factor for this concept regards the transportation. All-steel sandwich panels have today not yet been applied in bridges to the best of the author's knowledge, even though it has been proposed within the literature by several authors.



Figure 5. Possible bridge deck application for all-steel sandwich panel; a bascule bridge [12].

All metal sandwich panels can be manufactured using different joining techniques such as mechanical fastening, resistance spot welding, metallic bonding, adhesive bonding,

extrusion or laser-based welding. The earliest proposals of all-steel sandwich panels used mechanical fastenings, as Libove and Hubka [19] regarding applications for the aeronautical industry, in the form of rivets. During the late 1980s a research study was performed at the university of Manchester on resistance spot-welded corrugated steel sandwich panels, see Tan et al. [20]. Superplastically bonded steel sandwich plates was investigated by Ko [21]. Static- and fatigue loads were investigated by numerical analysis and experiments for adhesively bonded corrugated core steel sandwich beams by Knox et al. [22] and extruded aluminum sandwich plates has been addressed by e.g. Lok and Cheng [23]. Laser-welding makes it possible to create a continuous and robust connection between the core and the face plates. In the 1980s the development of laser-welded steel sandwich panels was led by the US navy (see Reutzel et al. [24] and Sikora and Dinsenhacher [25]). Since then, the development has been led by European research with application in ship-building in, for instance, Finland (Romanoff and Kujala [26], Romanoff [27], Jelovica [28] and Frank [26]–[29]), Poland (Kozak [30]) and Germany (Roland et al. [31]). Several European projects addressing the topic of laser-welded steel sandwich panels has been performed; see e.g. SANDWICH [32] and SANDCORE [33]. Application of steel sandwich panels can be found in a variety of industries as sub-way trains [34], fortification systems [35], ro-ro deck ramp in a ship [30], gravel truck container [36] etc.

1.2 AIM AND OBJECTIVE

The main aim of this thesis is to increase the knowledge regarding how to accurately model a CCSSP by using simplified approaches. Moreover, the aim is to refine the existing method referred to as the “homogenization approach” to accurately predict both deformations and stresses in CCSSPs with dual weld-lines. In relation to this aim, the present state of knowledge presented within the literature lacks in several aspects. Therefore, the following objectives are treated within the thesis:

- To present a methodology that can predict stresses in all of the constituent members of the cross section in conjunction with homogenized one-dimensional sandwich beam theory.
- To derive an accurate analytical model for the transverse shear stiffness in the weak direction of a CCSSP, valid for a dual weld joint configuration.
- To ensure that the analytical stiffness model can be used to accurately predict stresses in the constituent members of the cross section from shear action in the weak direction.
- To show the impact of the rotational rigidity of the weld region and to present a closed-form solution for its magnitude.

Furthermore, this thesis is aimed to present the natural spread of the production-dependent geometric properties in the core-to-face joint region from produced panels and to investigate the impact of their variation on fatigue-relevant stresses.

1.3 METHOD

The work presented in this thesis was started by a literature review that revealed several missing elements in order to accurately predict deformations and stresses in CCSSPs. To define the transverse shear stiffness of CCSSPs with dual weld lines, analytical methods were adopted. Verification of the analytical model was performed by numerical and experimental analyses. The closed-form solution for the weld region rotational stiffness was defined using numerical methods and both linear and non-linear regression analyses. For the work that

relates to the impact of variation of the production-dependent geometric parameters of the core-to-face joint in CCSSPs, measurements by optical microscope, 3D-scanning and manual measurement methods were used and the parametric study was performed using numerical analysis.

1.4 SCOPE

The scope of this thesis is limited to the weak direction load-carrying behavior of CCSSPs. For that reason, only sandwich beams are analyzed in this thesis. However, the shear stiffness model presented within this thesis, can be used also to predict deformation and stresses in panels. Furthermore, even though the directly applied load on a sandwich panel has a crucial impact on the state of stress in the panel, the homogenized beam approach presented within this thesis is limited to global load effects only. This also implies that the thick face effect that is related to loads applied in discrete points, is left outside the scope of this thesis. The study regarding the influence of variation of production-dependent geometric parameters of the core-to-face joints is limited to four manufactured panels for measurements and three different cases in the parametric study. Thus, the results from the parametric study should be considered in view of these limitations.

1.5 OUTLINE

Section 1. This section gives a background to the topic of this thesis and motivates the field of research.

Section 2. This section describes the manufacturing process for laser-welded corrugated core steel sandwich panels.

Section 3. In this section the simplified homogenization approach is described in detail and the research presented in Paper I and Paper II is motivated.

Section 4. This section displays the homogenization approach for a one-dimensional sandwich beam and verifies the methodology by numerical analysis and experimental results.

Section 5. In this section, the impact of variation of the production-dependent geometrical properties of the joint in CCSSPs, i.e. the work of Paper III, is summarized.

Section 6. The main conclusions from the three research papers presented within the thesis is summarized in this section.

2 MANUFACTURING OF ALL-STEEL SANDWICH PANELS

The key that enables the geometry of all-steel sandwich panels is a single-sided welding procedure. Paper III describes the production process of four CCSSPs. At present, laser-based welding processes are feasible procedures to create stake-welds. Figure 6 shows typical cross sections of two stake welds; a pure laser weld and a hybrid laser-arc weld. The hybrid process yields a wider weld due to the higher heat input and more pronounced weld reinforcement due to addition of material compared to the pure laser process. For the welds in Figure 6, the pure laser was executed by using 9kW laser power at 600mm/min welding speed, joining an 8 to a 6mm plate. The corresponding numbers for the hybrid process was 9kW laser power, 800mm/min and 6.7kW MIG/MAG-power for joining a 6 to a 5mm plate.

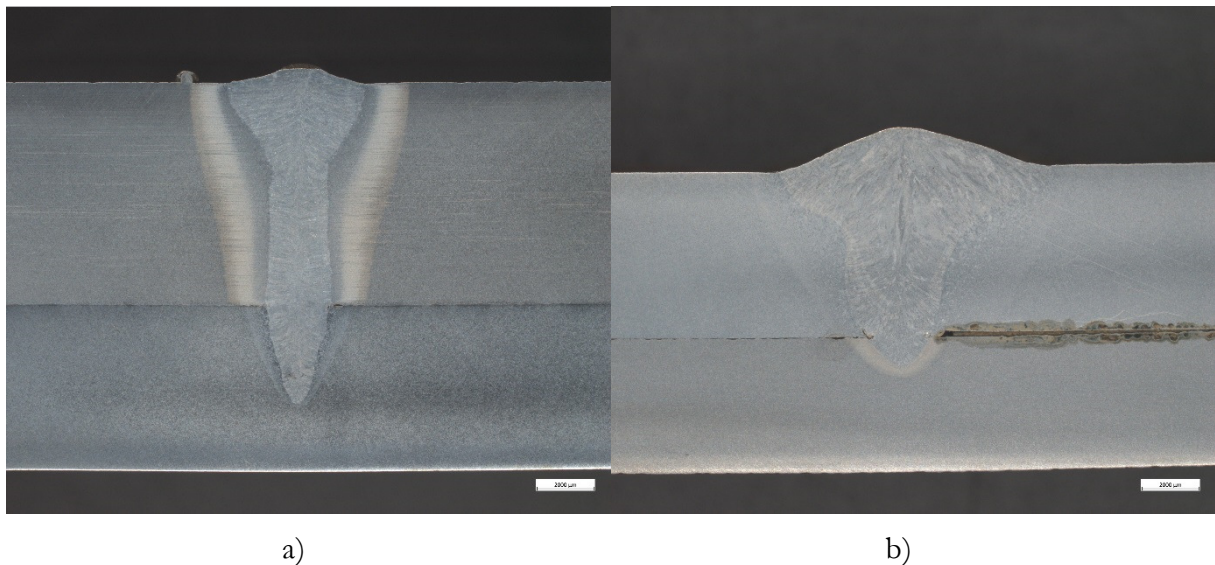


Figure 6. Microscopic images from stake-weld cross section; a) pure laser, b) hybrid laser-arc.

A continuous corrugated core can be produced in two ways, either by multiple single-wave channels joined together, or a continuous corrugated plate, as illustrated in Figure 7. The discrete channels need to be joined into a continuous core plate with a width equal to the panel width. For the core-to-core joints, where two unprepared plate sides are joined, a hybrid laser-arc weld is more suitable than a pure laser weld due to its capacity of filling the gaps and handling tolerances. Core to core welds are also needed for the case of a continuous core plates (Figure 7a) if the maximum width with respect to production of the corrugated plate is less than the final panel width.

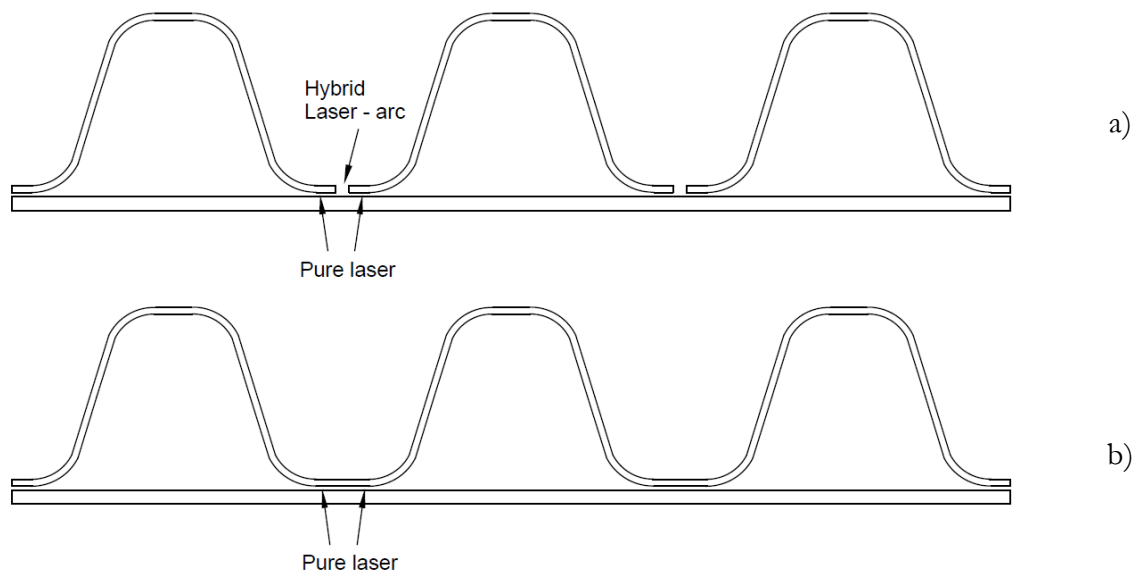


Figure 7. Two ways of manufacturing the continuous core; a) separate channels (continuity is created by hybrid laser-arc), b) continuous cold-formed core plate [Paper III].

When a pure laser stake weld is performed, a limited plate gap between the core and the face is of high importance for the final result of the weld geometry. Due to this aspect, a clamping-system is needed, see Figure 8 for the clamping system used in the manufacturing process presented in Paper III. Furthermore, in order to reduce the gap during production high demands on tolerances of the core shape is needed. A too large plate gap can impose a misshape of the weld, see Figure 9. The geometric misshape of the weld lead to a stress concentration at the intersection between the weld and the plate, and will likely lead to a reduced fatigue life. Furthermore, it can also lead to a reduced depth of penetration that also can affect the fatigue life.

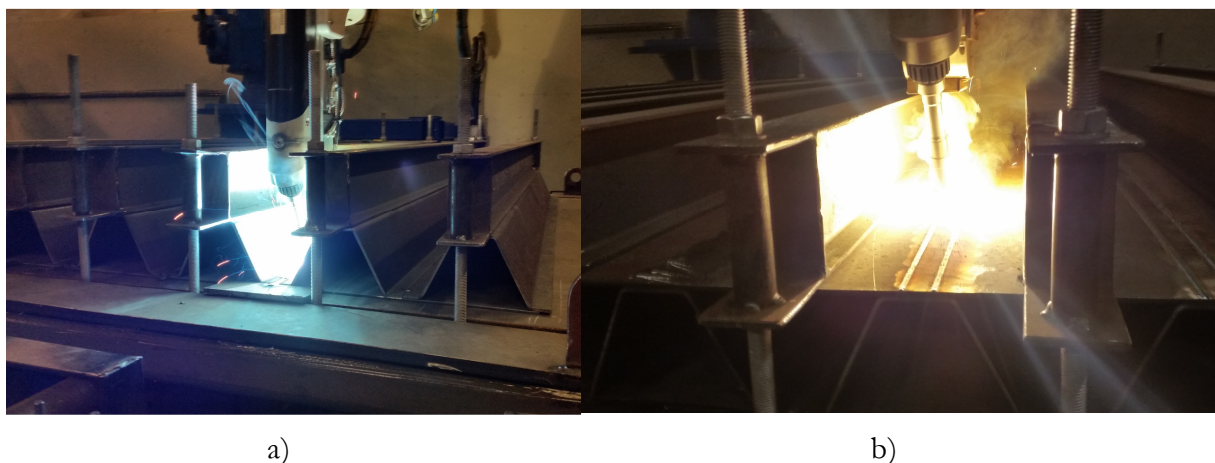


Figure 8. Clamping for welding; a) bottom face joint [Paper III], b) top face joint, photo: Kleven Verft AS.

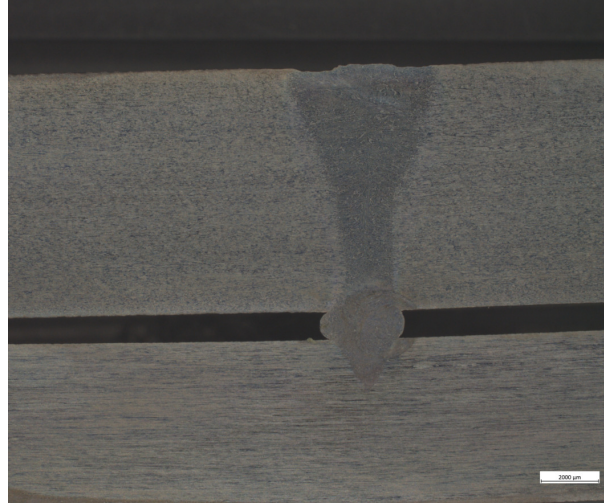


Figure 9. Misshaped weld due to large plate gap.

Figure 10 shows the cross sectional geometric properties of a corrugated core steel sandwich panel with dual weld-lines. The penetration depth of the laser welding process determines the maximum thicknesses that can be used in the core and face plates. Furthermore, when welding of the first side (e.g. core-to-bottom face joints) is performed, it can be executed from inside of the core and outwards. In such a case, the size of the welding-head imposes limitations on the relations between f , θ , b and d_w of Figure 10.

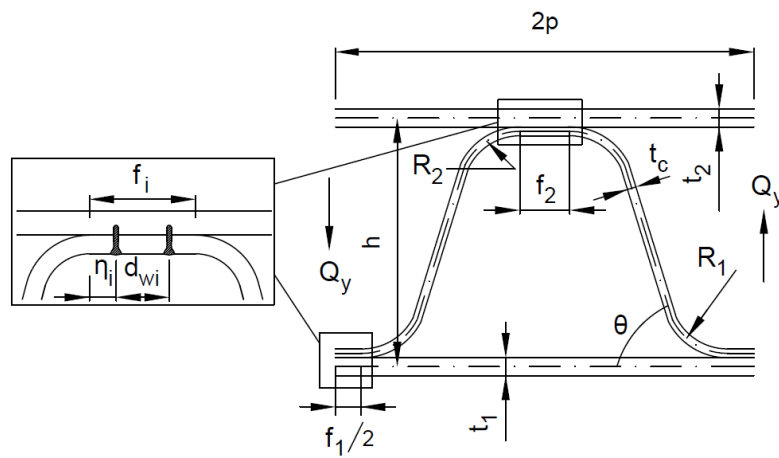


Figure 10. Cross sectional geometric properties of a corrugated core sandwich panel with dual weld lines [Paper I].

3 HOMOGENIZATION APPROACH

3.1 INTRODUCTION

A full three-dimensional (3D) analysis of a structural core sandwich panel (see a variety of examples in Figure 4) requires high computational effort. This is mainly due to the many distinct plate fields that require a specific number of elements to ensure accurate deformation and stress predictions. In addition, for design of bridges, several loads act simultaneously and the vehicle loads can be situated at any position of the bridge deck, where the most influencing vehicle position for the investigated part of the bridge needs to be determined. Thus, a structural analysis for design of a bridge should be executed a large number of times. However, a 3D sandwich panel can be simplified into a two-dimensional (2D) plate giving a large decrease in degrees of freedom that needs to be determined (see Figure 11). In order to utilize the 2D simplified analysis, the discrete structural core sandwich panel needs to be homogenized; i.e. the effective stiffness properties of the panel need to be calculated.

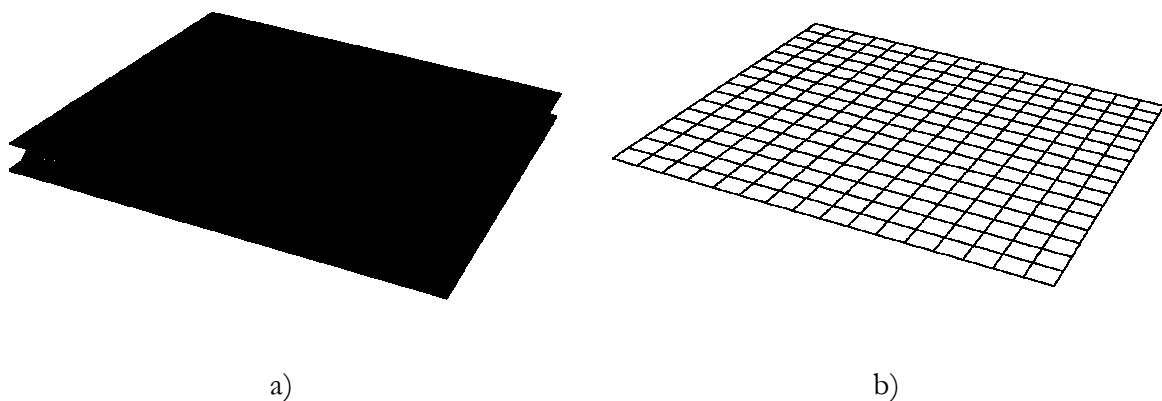


Figure 11. Principal mesh sketch; a) 3D model, b) an equivalent homogenized 2D model.

For an orthotropic sandwich plate subjected to out-of-plane loads, seven stiffness properties are needed (two bending, twisting, two shear and two Poissons ratios). All structural core steel sandwich panels are in their nature orthotropic plates. The faces are the main contributors to the second moment of area yielding approximately the same magnitude of bending stiffness in both directions. The source of orthotropy originates from the unidirectional core. The unidirectional core provides a continuous support for the face plates along a single line in the longitudinal direction of the core and the transverse shear stiffness in this direction is high. In contrary, the transverse shear stiffness in the orthogonal direction, where the connection points between the core and faces are discrete, is considerably lower. Thus, the transverse shear stiffness in the weak direction can play an important role for accurate deformation and stress predictions. Analyzing a structural core sandwich using a homogenous sandwich plate theory by including the bending, twisting, and out-of-plane shear stiffness components, both the orthotropy and the transverse shear deformations of the plate are accounted for. The output of the plate analysis is the plate center-plane deflections, as is shown in Figure 12a; i.e. an averaged global response. Nevertheless, for this method to be applicable in terms of sufficient accuracy, the number of core cells repetition on the width of the panel needs to be large. This enables the panel to have an approximately uniform distribution of stiffness.

After obtaining the center-plane deformations, the global sectional forces can be determined. Subsequently, the global sectional forces acting on the panel need to be applied to the discrete structure again in a separate analysis in order to determine accurate deformations and stresses in all the constituent plates of the sandwich panel (see Figure 12b). Due to the nature of homogenization, the approach lacks the possibility of determining stresses and deflections in the constituent members of the cross-section from directly applied load, see Figure 12c. If the effect of directly applied load is significant, as for bridge decks subjected to wheel pressure, this effect can be super positioned by a separate analysis, for design purpose. Figure 13 shows the homogenization procedure of plate bending analysis for a structural core sandwich plate.

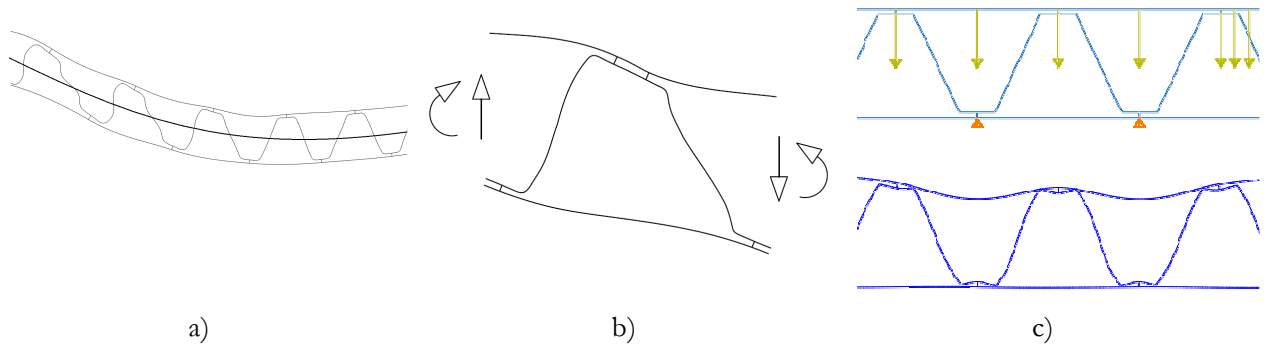


Figure 12. a) Center-plane deformations, b) deformation from directly applied load, c) deformations of the constituent members in the cross section of a corrugated core sandwich panel subjected to global bending and shear.

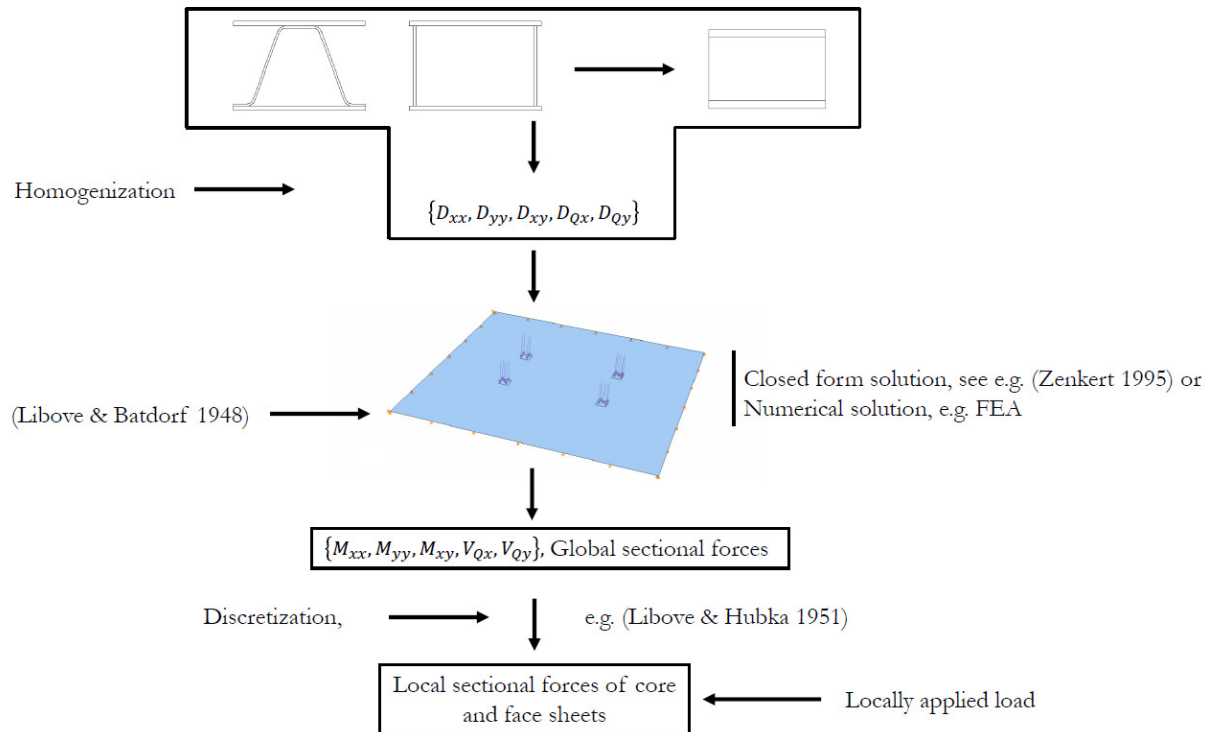


Figure 13. Flow-chart of bending analysis of discrete core sandwich plate.

In order to accurately predict the full state of stress distribution in a structural core sandwich panel subjected to out-of-plane loads, the homogenization procedure needs to be

performed with accurate sectional constants for the considered core configuration. Furthermore accurate analytical derivations for the sectional constants are needed in order to predict accurate stresses in the constituent members of the cross section from global sectional forces and moments. Directly applied loads need to be addressed separately. For web-core sandwich beams and panels, all of the above-mentioned aspects was addressed by Romanoff et al. in [27], [37]–[41]. Buannic et al. [42] presented a numerical approach to homogenization methods covering the center-plane deformations of a general structural core sandwich plate but excluding the effect of directly applied load. He et al. [43] presented a homogenization approach that follows the classical sandwich theory for global sectional force determination and used a simply supported continuous beam analogy for directly applied loads. However, to the author’s knowledge, the homogenization approach in conjunction with CCSSPs with dual-welded joints has not been addressed in the literature.

In addition to the possibility of fast calculations, the homogenization approach allows, by its several simplified sub-models, for an in-depth understanding of the structural response of the panel, compared to a full 3D numerical analysis approach.

3.2 SANDWICH PLATE THEORY

A sandwich plate in general consists of two outer facings and an intermediate core layer. In the general case, all three layers are homogenous, but not necessarily made of isotropic materials, see Figure 14. The basic principle of sandwich structures is that the outer faces carry the global bending moment and the core transfers the shear forces. A stiff material, often of a higher density, is used for the faces while the core consists of a lower density material, with considerably less stiffness. As the core has a low stiffness, shear-deformations of a significant magnitude can be induced and needs to be considered.

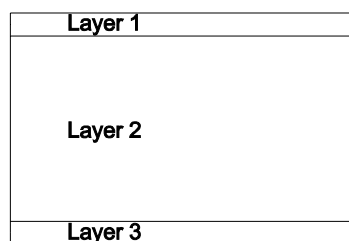


Figure 14. Sandwich cross section with homogenous layers [11].

The overall structural behavior of homogenous sandwich plates including bending, stability, dynamic characteristics, etc., has been collected in several textbooks; see e.g. Allen [44], Plantema [45], Vinson [46], Reddy [47] and more recently by Zenkert [34]. Literature review regarding a wide variety of sandwich plate theories was presented by Noor et al. [48], and Vinson [49].

For the case of an orthotropic homogenous sandwich plate subjected to out-of-plane loads, defined by its seven stiffness properties, Libove and Batdorf [50] derived a small deflection theory following the well-known Reissner-Mindlin kinematics (see Reissner [51] and Mindlin [52]). The plate theory of Libove and Batdorf [50] includes the transverse shear deformation contribution to the total out-of-plane deformation, and it was later extended to include curved sandwich panels by Stein and Mayer [53]. These first-order shear deformation theories (FSDT, i.e. linear distribution of in-plane deformations through the plate thickness yielding a constant shear strain distribution) are in the literature often referred to as classical

sandwich theory. Another approach to sandwich plate analysis is the ABD-matrix approach or general sandwich approach for anisotropic plates, which is an extension of classical lamina theory (see e.g. Vinson [46] or Reddy [47]). The ABD-matrix approach includes the B-matrix that enables coupling of the in-plane and bending actions, i.e. including the effect of diverging neutral- and center-plane (see e.g. Zenkert [34]). However, for CCSSP the B-matrix is a null-matrix if the cross section is symmetric and a panel analyzed by the classical sandwich theory and the ABD-matrix approach will be equivalent if FSDT is adopted. However, if large discrepancies with respect to the position of the neutral layer exist between the two orthogonal directions, excluding bending and membrane interaction can lead to considerable errors. Good agreement of the averaged response of CCSSPs has been reported in the literature using classical sandwich plate theory and full 3D numerical analysis or experimental analysis, see e.g. Dackman and Ek [17], Tan et al. [20] and Chang et al. [54].

Common for most sandwich plate theories is the assumption of thin faces, i.e. the faces act as membranes. This yields that the out of plane deformation from transverse shear has a singular derivative at discrete force application positions. The effect of thick faces at concentrated forces in sandwich beams with a homogenous core was addressed by Allen [44] and it was further explained in detail by O’Conner [55]. The thick face effect is likely to affect the results in CCSSPs for bridge applications close to supports if the support line and the corrugation direction is parallel. However, this topic is not addressed in this thesis. Thick face effects in conjunction with concentrated forces will be studied in the continuation of this study.

3.3 CROSS SECTIONAL PROPERTIES

The cross sectional properties of a sandwich cross section is used when considering homogenization of a structural core sandwich panel into an equivalent single layer plate analysis using FSDT. Furthermore, a proper analytical derivation of a cross sectional property will together with the corresponding global sectional force enable the calculation of the nominal stress distribution within the cross section in all of its constituent members. Cross sectional properties are defined in the literature for different types of steel sandwich cross sections. Common for structural core sandwich plates is that the stiffness properties are straight forward to derive, with exception of the transverse shear stiffness in the weak direction.

In 1950, Holmberg [56] published the derivation of the transverse shear stiffness for web-core sandwich beams. Lok et al. [57] presented a further developed derivation of the web-core transverse shear stiffness. Kujala and Klanac [58] introduced an expression for non-uniform web-core cross sections. Furthermore, Romanoff et al. [38] enhanced the definition of the transverse shear stiffness by incorporating the rotational rigidity of the weld region in the core-to-face plate connection.

For corrugated core sandwich cross sections, Libove and Hubka [19] derived analytical expressions for all cross sectional constants. For the transverse shear stiffness in the direction perpendicular to the core, this work was performed using Euler-Bernoulli beam theory and a single rigid connection between the face-plates and the core. When the global transverse shear force is known from the homogenous beam or plate analysis, all local sectional forces of the constituent members of the cross section can be calculated using the derivation of Libove and Hubka [19]. Furthermore, Nordstrand [59] derived the shear stiffness in the weak direction, also using a single rigid connection between the face-plates and the core, but extending the theory of Libove and Hubka [19] to include curved beam theory according to

Timoschenko [60]. However, in Nordstrand [59], only symmetric cross sections were considered. Atashipour and Al-Emrani [61] derived a transverse shear model in the weak direction that include the shear deformations of the constituent members of the cross section and composite material properties. The derivations of Nordstrand [59], Libove and Hubka [19] and Atashipour and Al-Emrani [61] was performed using a single rigid connection between the face-plates and the core, and to the authors knowledge, no model that includes dual connection lines between the core and face plates exists in the literature.

Sandkvist and Palmgren [62], and Nilsson and Al-Emrani [11] showed that for bridge applications, usage of two weld lines between the core and the faces compared to a single weld line will lead to large decrease of stresses in the weld region, yielding an increased fatigue life. These analyses were performed without contact interaction between the core and the face plates. Furthermore, Persson [63], and Nilsson and Al-Emrani [11] showed that, implementation of a single rigid connection between the core and the face plates will lead to overestimations of the transverse shear stiffness in real sandwich plates. In fact, the response of the real structure will likely be in-between that of a model with a rotational hinge and a rotationally rigid core-to-face interaction. Furthermore, with respect to laser-welded web-core sandwich panels, the influence of including the rotational rigidity of the weld region on the stress prediction was shown by Romanoff and Kujala [38]. In a corrugated core steel sandwich panel with dual weld lines, the slenderness ratio (length-to-thickness ratio) of the constituent members of the cross section may be small, i.e. less than 10. Thus, shear deformations in the constituents may affect the shear stiffness of the panel and the stress distribution within the cross section.

In Paper I, a new model for the transverse shear stiffness in the weak direction for CCSSPs with dual weld connections at each core-to-face joint is presented. The analytical solution is based on the direct stiffness approach and it adopts the minimum potential energy theorem in order to compose the stiffness matrix for the non-straight core member. Timoshenko beam theory is adopted in the analytical model, i.e. the effect of shear deformations in the individual members are included. Furthermore, a rotational spring is included in the analytical model in order to account for the rotational rigidity of the weld region. The accuracy of the analytical model for the transverse shear stiffness is to a large extent dependent on the degrees of freedom included in the model. A CCSSP under pure transverse shear is shown in Figure 10 and the structural setup and the included degrees of freedom for the shear stiffness derivation in Paper I is shown in Figure 15. Paper I shows that the accuracy of the presented analytical model is high in comparison with beam element finite element analysis (FEA), thus, the chosen degrees of freedom are adequate to represent the sandwich panel under pure shear. A closed-form solution for the magnitude of the rotational spring is presented in Paper II. The closed-form solution for the rotational spring stiffness is based on a large set of solid element FEAs and regression analysis post-processing.

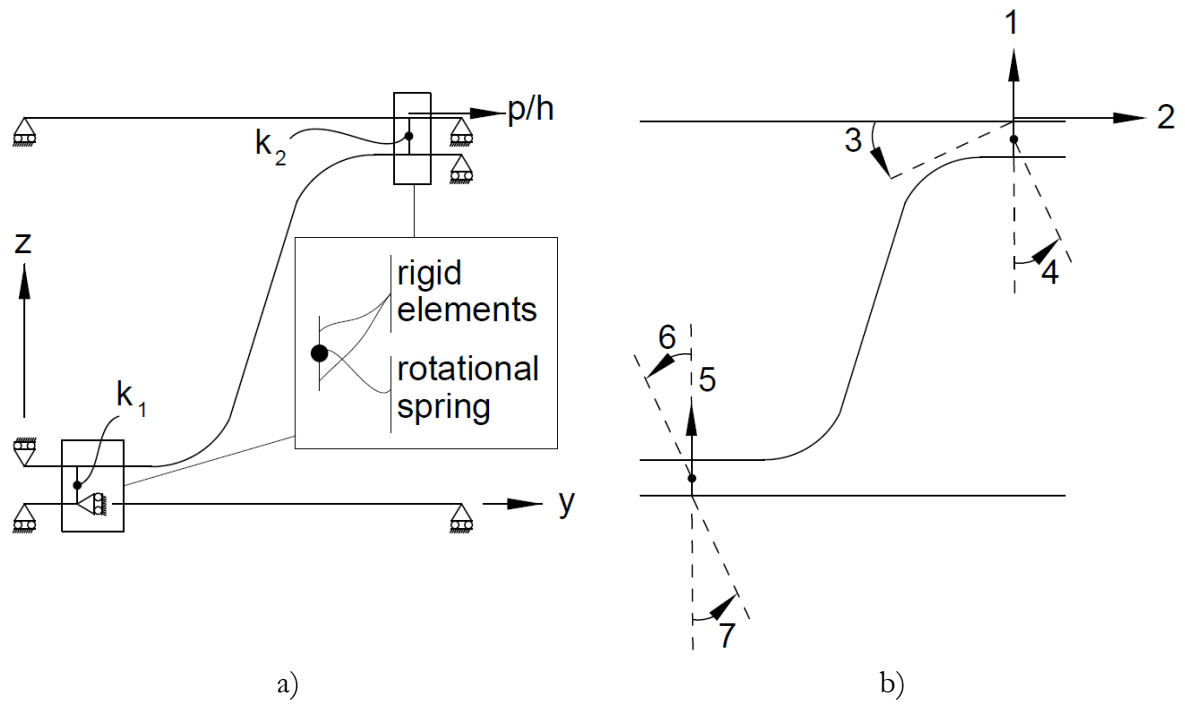


Figure 15. a) Structural setup for derivation of the transverse shear stiffness b) included degrees of freedom. [Paper I].

4 VERIFICATION OF THE BEAM HOMOGENIZATION APPROACH

As stated in Section 3, an all-steel sandwich panel can be analyzed using a simplified approach using (1) a simplified global analysis, and (2) a separate analysis for calculations of stresses in the constituent members of the cross section due to global load effects as well as (3) a separate analysis regarding the directly applied load. However, the directly applied load is left outside the scope in this section. The special case of load distribution in the weak direction is studied, i.e. a beam from a CCSSP section is the focus of this case study. Thus, this section presents a methodology that adopts the homogenized beam approach to be valid for corrugated core cross sections with dual weld-lines. Furthermore, the accuracy of this methodology is verified by numerical analysis and experimental results in a case study.

4.1 NUMERICAL ANALYSES

In this section, three different levels of structural analysis of a simply supported corrugated core steel sandwich beam are compared: (1) a 2D continuum element FEA, (2) a 2D frame FEA and (3) a one-dimensional (1D) analytical homogenized beam model. The geometric properties of the studied beam is shown in Table 1 and the notations are given in Figure 10. In this section the stresses in the outermost fiber of the top face at a core-to-face joint at a clear distance from both loads and BCs is studied. All models in this case study are linear. The three compared models, the studied output area, loads and BCs are shown in Figure 16.

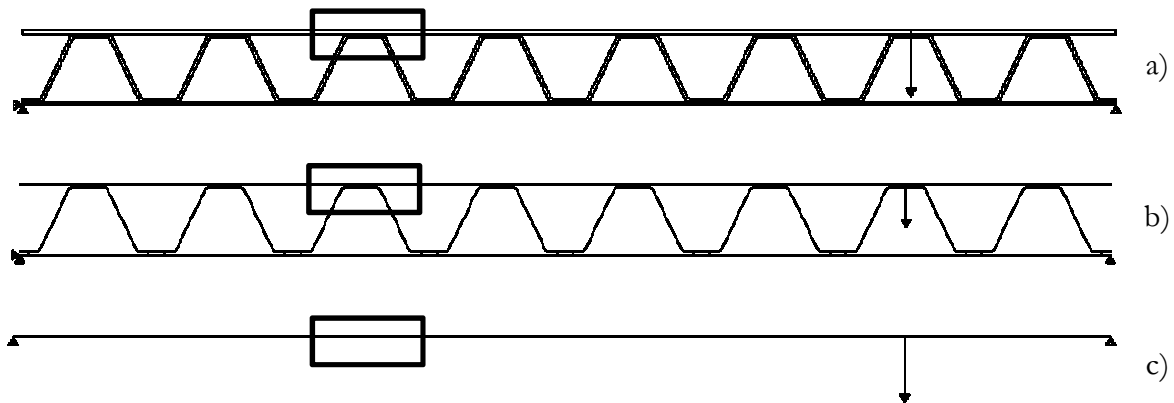


Figure 16. Three different levels of structural analysis; a) 2D solid element FEA, b) 2D beam element FEA, c) analytical homogenous beam analysis. The rectangular boxes indicates the investigated area.

Table 1. Geometric properties for the case study beam.

t_1	t_c	t_2	b	θ	$f_{1,2}$	$d_{w1,2}$	$R_{1,2}$	$2p$	n_{cells}	t_w	b
[mm]	[mm]	[mm]	[mm]	[°]	[mm]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]
5	6	8	132	64.4	60	30	7.4	253	8	1	190

For the analytical model, a homogenized beam is studied and the resulting sectional forces and moments are used to calculate the stresses in the constituent members of the beam. The global bending moment yields an axial force and thereby a normal stress in the top face. This stress is calculated by classical sandwich theory for homogenous cross sections as $(M/b)/(t_2b)$ where M and b are the global moment and the beam width, respectively. In each plate field,

i.e. between two core-to-face connection points, this stress is constant. As this stress is constant over a plate field and M is linear along the beam length, this stress is calculated with M from the centre-point of respective field. The top face stresses that originate from global shear action are calculated according to Paper I and the results are compared with the model of Libove and Hubka [19]. The weld region rotational stiffness used in this case study, both for the analytical and 2D frame model, is determined according to Paper II as 4.2 kNm/rad.

Figure 17a shows a comparison between the two 2D FEA models and the two analytical models where one uses a stress calculation from global shear according to Libove and Hubka [19] and the other adopts the model presented in Paper I. Figure 17a shows that using the model of Libove and Hubka [19] for dual welded CCSSPs can lead to large error considering stress predictions, which was expected. Figure 17a also shows that the two 2D FEA models are in perfect agreement, except at the position of the welds. At the position of the welds, there is a principle discrepancy between the two models where the continuum element model for the top face stress shows a smoothed distribution compared to the discrete point stress change for the frame case. Thus, stress predictions performed with a top face element, that lacks ability in predicting the correct through-thickness stress distribution, will lead to conservative results.

Figure 17a also shows that there is a discrepancy between the analytical model in conjunction with the shear model from Paper I and the 2D frame model. As the model in Paper I is verified to be accurate, this discrepancy is due to the simplified stress calculation from global bending moment using classical sandwich theory. The discrepancy is small when considering normal stresses in the span between two joints. However, the normal stress discrepancy at the discrete point of the weld is significant. This indicates that the global moment has an effect on the nominal stress in the weld. To the author's knowledge, no analytical derivation for the bending stiffness of CCSSPs with dual weld lines, exists within the literature, corresponding to the shear stiffness model of Paper I. In the absence of an analytical model, a 4-point bending numerical 2D frame model is executed. Thus, a state of pure moment between the two external loads in the 4-point bending model is analyzed. The 4-point bending model shows that the global bending yields a small decrease in axial force and a significant increase in local bending moment in the beam segment between the welds. Figure 17b shows that using the analytical model (1D homogenized beam) that adopts the shear model of Paper I in conjunction with the numerical model for global moment yields perfect agreement to the 2D frame FEA. This was also concluded by Diffs and Ro [64].

Figure 17c shows the top face stresses for two special cases of the FEA frame model; one where the weld region rotational stiffness is assumed to be zero (hinge) and one where full rotational interaction between the core and the face plates is assumed (rotationally fixed). The stresses in the span between the joints show a modest discrepancy between the two cases. However, at the weld where the stresses change in a discrete point, a major discrepancy is shown. Thus, force transfer between the core and the faces – i.e. the nominal state of stress in the weld – is highly dependent on the rotational spring. In fact, in this special case, the nominal normal stress in the weld increases with 75% for the case with a fixed connection compared to the model with a rotational hinge.

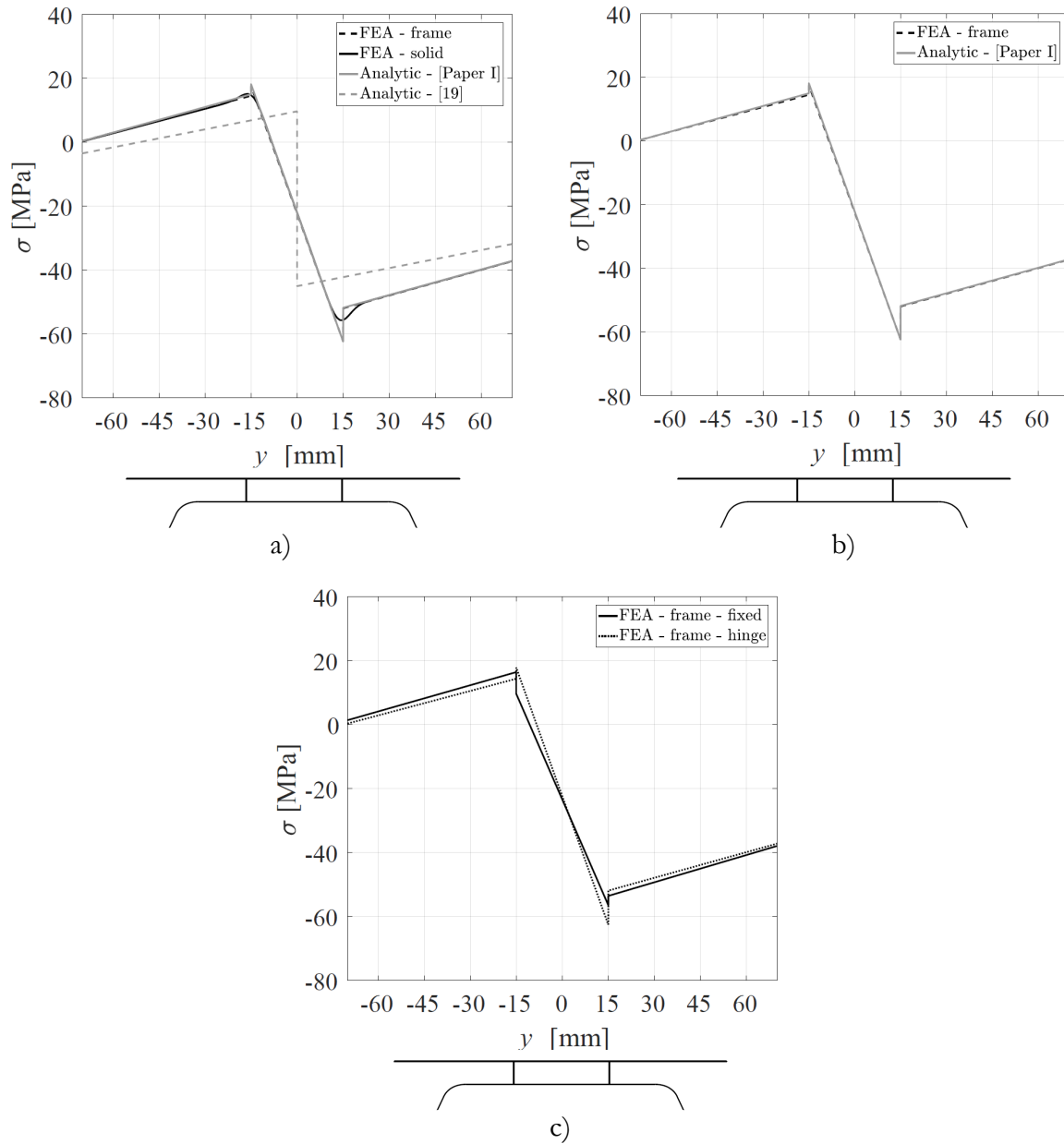


Figure 17. Normal stress distribution in the top fiber of the top face; a) comparison between 2D solid and frame numerical models and 1D analytical models based on classic sandwich theory calculation of stresses from global moment, b) comparison between numerical 2D frame model and 1D analytical model where a separate analysis for calculation of stresses from global moment was performed, c) 2D numerical model with rotationally fixed core-to-face plate interaction at the welds compared to equivalent model with rotational hinge.

4.2 EXPERIMENTAL STUDIES

In order to verify the developed numerical and analytical analyses, experiments are conducted. The test setup is identical to that of the above presented case study and it is shown in Figure 18a. Furthermore, the geometric properties of the beam are given in Table 1. The experiment is repeated for two identical beams of conventional structural steel S355, herein denoted as Beam 1 and Beam 2. For the output region, highlighted in Figure 16, the positions and names of the strain gauges in Beam 1 are shown in Figure 18b. The ten strain gauges 4-13 are mounted in a single multi-channel device with an intermediate spacing of 2

mm between the gauges. The multi-channel device is located directly above the right weld line. For Beam 2, strain gauges corresponding to position 2, 3 and 14 in are installed.

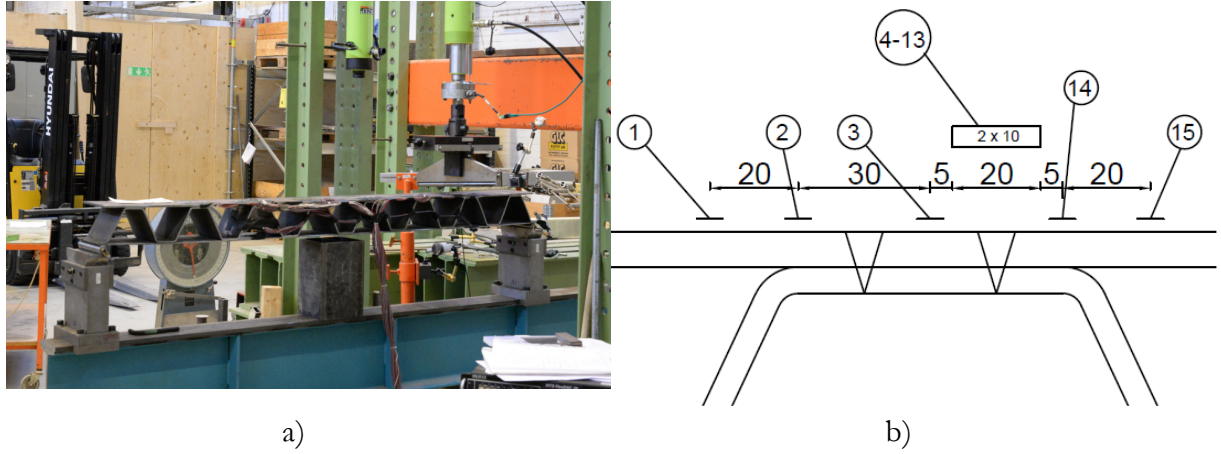


Figure 18. Experiments; a) test setup, b) strain gauges at output joint.

The strain measurements from gauge 15 (Figure 18b) is shown in Figure 19a as a function of applied load. Figure 19a shows that the strain is close to linear, however with a modest curvature. The origin to this non-linearity is not assessed in detail in this thesis, but can originate from both measurements and structural aspects. In order to display this non-linearity, a curve-fit of each strain signal is executed. The analytical expression related to the strain signal is then differentiated. The derivative of the strain signal is used to calculate a final stress for a 30kN applied load. Figure 19b shows the final normal stress from an applied load of 30kN, calculated by a linear load-stress-strain relation and using the derivative of the strain distribution of gauge 15. Thus, each strain signal yields an upper and a lower bound for the stress prediction (~ 42 and 46 MPa for gauge 15).

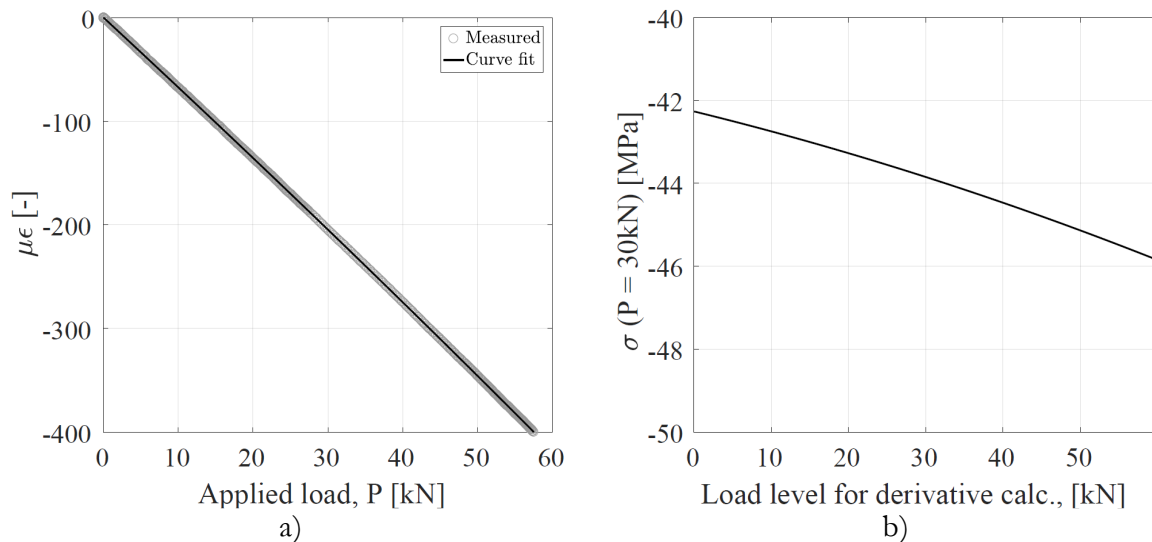


Figure 19. a) Measured micro-strain as a function of applied load and curve-fitted function, b) final stress at a load level of 30kN as a function of the load-level for the derivative calculation.

Figure 20 shows the stress distribution on the surface of the top face as obtained from numerical analysis and measurements at a load level of 30kN. For the experimental results, the upper and lower bound stresses are indicated. The circular points in Figure 20 indicates the stresses when the derivative of the strains at a load level of 10kN is used. Apart from gauges 4-13, which belong to the multi-channel device, good agreement between the experiments and the numerical analysis is shown with a maximum deviation of $\sim 4\text{MPa}$ ($<10\%$). Gauges 4-13 show a difference in stress distribution compared to the numerical analysis. A clear explanation for the difference in measured and calculated strains in this local area has not been found and further, more detailed, analysis is needed to have a better insight into this problem.

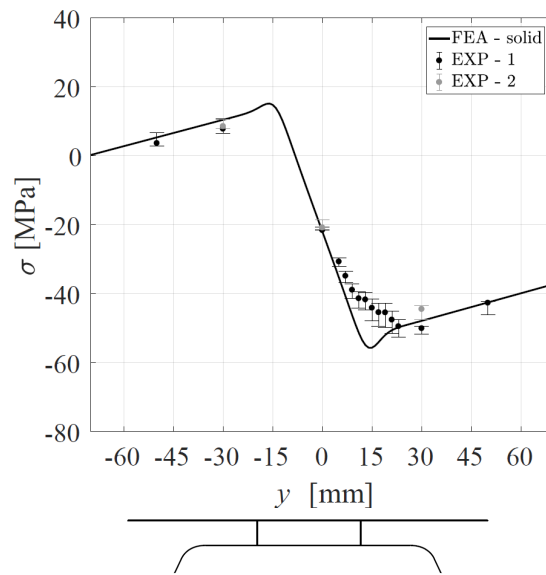


Figure 20. Stress distribution for the case study beam by numerical analysis and experiments.

5 THE IMPACT OF VARIATION OF PRODUCTION-DEPENDENT PARAMETERS OF CCSSP JOINTS

The nature of welding induces a spread of the geometric properties in the joint region in laser-welded CCSSPs. Several conditions from the welding process affects the final geometry of the joint as clamping, welding speed, etc. In CCSSPs three geometric properties of the joint region are dependent on the production conditions; t_w , e_w and h_g , denoting the weld width, weld misalignment and the plate gap height between the top face and core, respectively; see Figure 21. In order to ensure functionality of a sandwich panel for its entire service life, the natural spread of the production-dependent parameters from the used manufacturing process need to be determined and the effect of the spread of the parameters needs to be known.

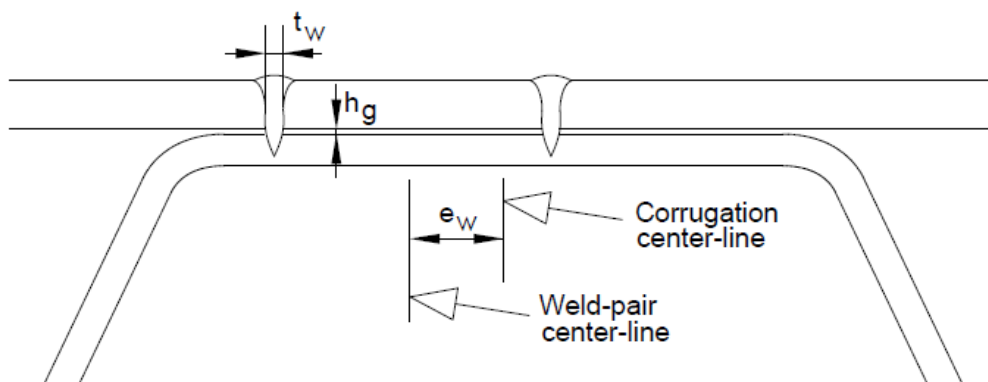


Figure 21. Joint region production-dependent geometric properties [Paper I].

Paper III addresses the impact of the variation of production-dependent geometric properties of CCSSP core-to-face joints with respect to fatigue-relevant stresses. The aim of Paper III is to determine what stresses in the weld region are sensitive to a misfit between the idealized and the real geometry. In order to fulfil this aim, four sandwich panels were manufactured and the geometry of the weld region was quantified. The spread of the geometric properties of the joints was used in a parametric study based on FEA. The focus of this parametric study is the transfer of load effects in the weak direction of a CCSSP, and therefore, a beam from a transverse section of a panel is studied.

For the parametric study in Paper III, three different beams with two different sets of loads and boundary conditions are studied. Load cases 1 and 2 concern isolated effects of directly applied load (global action is prevented) and pure global load effects, respectively. Furthermore, all models are executed both by including and excluding contact interaction between the top face and core plate. Two normal stresses at the position of the welds, in the outermost fiber of the top face and the core, and the principal stress in the weld notches are the chosen outputs in the study. The fatigue-relevant output stresses and their corresponding crack modes are shown in Figure 22. With a basis of the measured joint region geometries, three levels for each of the three parameters are decided to be included in the parametric study: [1 mm, 2.5 mm, 4 mm], [-2 mm, 0, 2 mm] and [1 μ m, 50 μ m, 100 μ m] for; t_w , e_w and h_g , respectively. This parametric study includes the result of 324 2D continuum element FEAs.

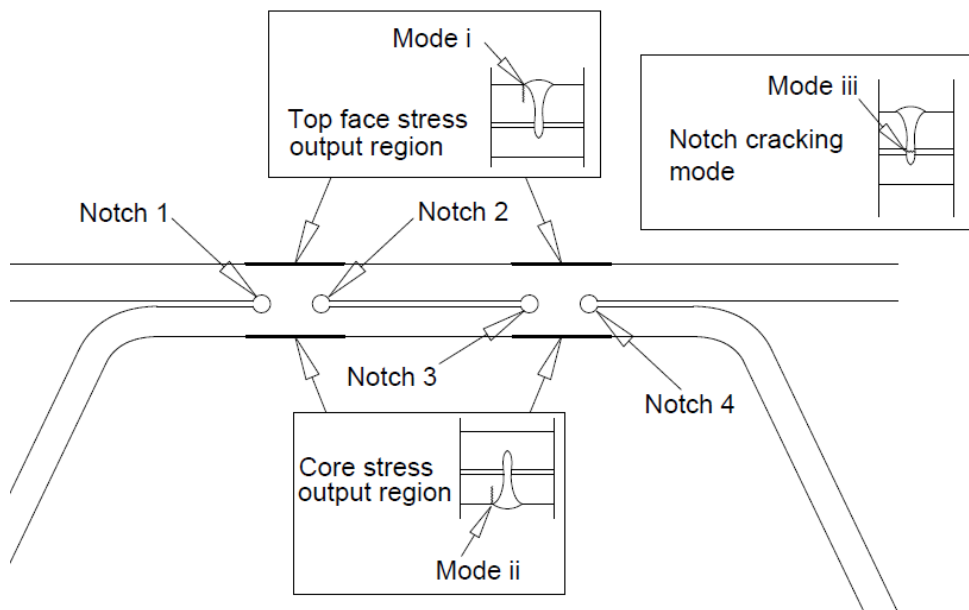


Figure 22. Fatigue-relevant output stresses of the parametric study and their corresponding crack-modes [Paper III].

The results – for the three investigated beam cases – show that the weld misalignment have a modest impact on the top face normal stresses. However, the impact on the notch and core stresses is shown to be significant. Considering isolated global load effects, a weld misalignment of 2 mm can yield up to a 40% increase in notch stress. The weld misalignment is shown to have a more pronounced effect for the case of pure global load effects compared to the case of isolated effect of directly applied load. The reason for the significant impact of the weld misalignment is related to the high stiffness of the joint region. When the external load enforces unequal rotations of the two welds in a weld pair, restraint shear forces act on the welds, leading to high fatigue-relevant stresses.

In Paper III it is shown that the weld width has a small effect on the top face and core normal stresses in the vicinity of the weld. However, a considerable effect of a change in weld width on the notch stresses is shown. Furthermore, the results show that an increase in the weld width can both increase and decrease the notch stress. This may be due to the fact that increasing the weld width increases the core-to-face interaction simultaneously as the section modulus and area of the weld itself increases.

When contact interaction between the core and the face plate is excluded in the analysis, the plate gap has no or very modest impact on all investigated output stresses. However, when contact interaction is included in the analysis, the gap size has a major impact on all three investigated stresses. This is because the gap size is the main influencing factor for determining at which load-level contact between the core and faces occur. For the load case with isolated effect of directly applied load, contact always decrease the fatigue-relevant stresses. However, for the case of pure global load effects, it is shown that contact interaction can lead to increased stresses.

6 CONCLUSIONS

The main focus of this thesis was on the weak direction out-of-plane load-carrying behavior of CCSSPs subjected to out-of-plane loads. This thesis aimed to further develop the homogenized beam approach to accurately predict deformation and stress in a corrugated CCSSPs with dual weld lines subjected to global load effects. From the results presented within this thesis it was concluded that:

- The refined homogenized sandwich beam approach, presented in this thesis, was shown to predict stresses accurately by verification using numerical analysis and experiments.
- The analytical transverse shear model presented within this thesis was shown to yield accurate predictions with respect to both stiffness and stresses in the constituent members of the cross section.
- It was shown that global bending moment in the weak direction can have a significant effect on the nominal stresses in the welds.
- A closed-form solution for the rotational stiffness of a laser stake weld was presented. It was shown that this rotational stiffness has an impact on the stress predictions for CCSSPs. The solution was shown to predict the rotational stiffness with high accuracy.

From the three studied cases of which the impact of variation of the manufacturing-dependent geometric properties of the weld region was investigated, it was concluded that:

- A considerably small weld misalignment can lead to significant increases in fatigue-relevant stresses in the vicinity of the welds.
- Increasing the weld width can lead to both increased and decreased fatigue-relevant stresses.
- Contact between the core and the faces in the sandwich panel yields decreased fatigue-relevant stresses for all investigated geometrical cases when considering isolated locally applied load and restrained global action. However, when pure global load effects were investigated, contact was seen to yield increased fatigue-relevant stresses in some cases.

7 FUTURE WORK

Within this thesis, the directly applied load (e.g. from wheel pressure) onto the sandwich beam was excluded. However, this aspect has been shown to have a major impact on the state of stress in a sandwich beam or panel. Thus, the effect of directly applied load on a sandwich beam or panel is suggested as a future research topic. Furthermore, the effect of global bending moment on the sandwich beam was in this thesis calculated by numerical analysis. However, a suggested topic for further research is to derive an analytical solution for this bending stiffness in the weak direction, analogous to the model for transverse shear presented within this thesis. Such model should also deliver accurate predictions of load effects in the welds and the constituent plates of the sandwich panel. Verifications of the refined homogenized beam approach, i.e. the transverse shear model, was made with respect to top face stresses by using numerical analysis and experiments. This verification should be extended to include other parts of the cross section. Furthermore, and of most importance, the method presented in this thesis should be extended to a panel-level.

Fatigue was in this thesis pointed out as a key topic for steel bridge decks and the effect of geometric properties of the core-to-face joint was investigated with respect to fatigue-relevant stresses. However, fatigue strength was not addressed in this thesis and it is a topic for future research.

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