Department of Applied Mechanics

Global buckling response of web-core steel sandwich plates influenced by general corrosion

Jasmin Jelovica

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 140/2014

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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 216 at Otakaari 4 (K1 building) on 6th of November, 2014, at 12.

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Aalto University publication series
DOCTORAL DISSERTATIONS 140/2014

ISBN 978-952-60-5860-3
ISBN 978-952-60-5861-0 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Unigrafia Oy
Helsinki 2014

Finland

NORDIC ECOLABEL
441 697
Printed matter

Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Jasmin Jelovica

Name of the doctoral dissertation
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Publisher School of Engineering

Unit Department of Applied Mechanics

Series Aalto University publication series DOCTORAL DISSERTATIONS 140/2014

Field of research Naval Architecture

Manuscript submitted 16 June 2014 **Date of the defence** 6 November 2014

Permission to publish granted (date) 18 August 2014 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

A web-core steel sandwich plate is a lightweight, orthotropic structure. The constituent thin plates (2-4 mm) are joined by laser-welding. This thesis investigates the buckling and post-buckling behaviour of slender web-core sandwich plates loaded in the direction of the web plates. The influence of corrosion on the plate buckling is studied via finite element method (FEM). The corrosion scenario used is based on experimental observations from specimens submerged into the sea for 1 and 2 years. The plate strength analyses are performed with two methods: FEM having shell element mesh of the three-dimensional topology and the equivalent single-layer theory (ESL). In the later, the sandwich plate is represented with constant, homogenised stiffness coefficients, which are related to physical properties of the structure.

The first buckling mode of slender web-core sandwich plates is characterised with global deformation between the edge supports. The buckling strength depends on the bending and transverse shear stiffnesses. This thesis revealed that the buckling strength is very sensitive to the variation in transverse shear stiffness opposite to the web plate direction, D_{Qy}, especially in sandwich plates with high bending stiffness. Furthermore, the stiffness of the sandwich plate as a whole in the post-buckling is controlled by that of the in-plane stiffness. The web plates impose high, shear-induced, secondary bending stresses on the face plates and these were found to be important for accurate estimation of the onset of yielding. The deformation resulting from the secondary bending of the face plates makes the unloaded edge stiffer. Although membrane stress can be higher there, local buckling during global post-buckling occurs further away where the secondary deformations are smaller, primarily in the centre of the face plate ($x=a/2$, $y=b/2$). Furthermore, the corrosion tests revealed that the cross-section is primarily affected by general corrosion. Under this circumstance, the reduction of the thickness of the face and web plates reduces the stiffness coefficients and also the buckling strength linearly. The buckling strength reduces rapidly, especially because of the reduction in the transverse shear stiffness D_{Qy}. The reduction of buckling strength doubles if, in addition to the outer faces, corrosion also occurs inside the sandwich plate. Beam bending tests also showed rapid reduction of the ultimate strength but, in addition, that it can be maintained using different protection methods. The results thus indicate that the protection against corrosion should be carefully performed.

The future work will involve improving the accuracy of the ESL theory in the presence of local buckling.

Keywords Buckling, Post-buckling, Sandwich plate, Corrosion, Steel, Web-core, Equivalent single-layer

ISBN (printed) 978-952-60-5860-3 **ISBN (pdf)** 978-952-60-5861-0

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2014

Pages 95

Acknowledgements

My work on this thesis has been funded by the Ministry of Education of Finland through the National Graduate School in Engineering Mechanics, National-funded project SUTERA, EU-funded project ThroughLife, Finnish Maritime Foundation, Sustainable Breakthrough Innovations project, funded by the Finnish Metals and Engineering Competence Cluster (FIMECC) and Finland Distinguished Professor (FiDiPro) project "Non-linear Response of Large, Complex Thin-Walled Structures" funded by the Finnish Funding Agency for Innovation (Tekes), Deltamarin, Napa Ltd, Koneteknologiakeskus Turku, Ruukki and STX Finland. Their financial support is gratefully acknowledged. Appreciation is also due to CSC – IT Centre for Science Ltd. for providing ABAQUS software license. Meyer Werft is thanked for producing the test specimens.

I would like to sincerely thank my supervisor and one of the instructors, Jani Romanoff, for his support throughout the thesis process. Thank you Jani for patience and guidance, your advices were very helpful in numerous occasions. I am also grateful to my former supervisor, Petri Varsta, for his help on the direction of research. Petri took over the position of the dean of the school about one year after my start, but remained involved in the progress of the thesis.

I am grateful to my second instructor Heikki Remes for guidance and support. I am also grateful to Sören Ehlers and Jari Aromaa for their advices in joint publications. I would like to thank my colleagues at the Department of Applied Mechanics for their friendship and guidance in different stages of this process: Alan Klanac, Darko Frank, Kristjan Tabri, Mihkel Kõrgesaar, Ingrit Lillemäe, Pauli Lehto, Anghel Cernescu, Bruno Reinaldo Gonçalves, Eero Avi, Olof Forsén, Alp Karakoç, Susanna Hurme, Jarno Jokinen, Halid Can Yildirim, Pentti Kujala, Seija Latvala, Leila Silonsaari and Pentti Tukia. I would also like to thank Prof. J.N. Reddy for reviewing the manuscript of the last paper, for insights on plate theories and interesting discussions about science and life in general. Thanks go to Reijo Lindgren for his help with the connector element in Abaqus software.

I would also like to thank my parents and friends for giving me encouragement in numerous occasions. The greatest support came from my dear wife Bahare who I was lucky to meet during the work on this thesis.

Espoo, 2014

Jasmin Jelovica

Contents

List of abbreviations and symbols

Each publication introduces its list of symbols or in the case of Publication 3, they are explained in the corresponding text. The following abbreviations and symbols appear in the thesis summary:

2D	Two-dimensional
3D	Three-dimensional
a, b	Length and width of the sandwich plate
h, h_c	Height of the sandwich plate and height of the core
m, n	Number of buckling half-waves in x- and y-direction
s	Spacing of web plates
u, w	Displacement of the sandwich plate in x- and z-direction
w_o	Initial magnitude of imperfection
t_f, t_w	Thickness of the face plate and thickness of the web plate
t_{lw}	Thickness of the laser weld
A_{ij}, B_{ij}, D_{ij}	In-plane, coupling and bending stiffnesses, i,j=1,2,3.
D_{Qx}, D_{Qy}	Transverse shear stiffness in x- and y-direction
E	Young´s modulus
ESL	Equivalent single-layer
F	Force acting on the plate
FEM	Finite element method
FSDT	First-order shear deformation theory
IMO	International Maritime Organization
N_o	Buckling strength of a sandwich plate
σ_y	Stress component in y-direction
σ_f	Yield strength of the material
ν	Poisson ratio

List of publications

This doctoral dissertation consists of a summary and of the following publications which are referred to by their numerals in the text:

1. Jelovica, Jasmin; Romanoff, Jani; Ehlers, Sören; Varsta, Petri. Influence of weld stiffness on buckling strength of laser-welded web-core sandwich plates. Journal of Constructional Steel Research, volume 77, pages 12-18, 2012.

2. Jelovica, Jasmin; Romanoff, Jani. Load-carrying behaviour of web-core sandwich plates in compression. Thin-Walled Structures, volume 73, pages 264-272, 2013.

3. Jelovica, Jasmin; Romanoff, Jani; Ehlers, Sören; Aromaa, Jari. Ultimate strength of corroded web-core sandwich beams. Marine Structures, volume 31, pages 1-14, 2013.

4. Jelovica, Jasmin; Romanoff, Jani; Remes, Heikki. Influence of general corrosion on buckling strength of laser-welded web-core sandwich plates. 33 pages. Journal of Constructional Steel Research, volume 101, pages 342-350, 2014.

Author’s contribution

Publication 1: Influence of weld stiffness on buckling strength of laser-welded web-core sandwich plates.

The author carried out the analyses and wrote the manuscript. Romanoff, Ehlers, and Varsta made valuable comments on the analyses and manuscript.

Publication 2: Load-carrying behaviour of web-core sandwich plates in compression.

The author carried out the analyses and wrote the manuscript. Romanoff made valuable comments on the analyses and manuscript.

Publication 3: Ultimate strength of corroded web-core sandwich beams.

The author prepared the specimens and carried out the mechanical testing, tensile tests, and geometrical measurements. He also carried out the numerical analysis and wrote the manuscript. Romanoff and Aromaa planned the corrosion and mechanical testing and made valuable comments on the manuscript. Ehlers made valuable comments on the manuscript.

Publication 4: Influence of general corrosion on buckling strength of laser-welded web-core sandwich plates.

The author carried out the analysis and wrote the manuscript. Romanoff and Remes made valuable comments on the manuscript.

Original features

The following features are believed to be original in this thesis:

1. The influence of stiffnesses on the buckling strength (Publication 1, Publication 2) and post-buckling behaviour (Publication 2) of slender laser-welded web-core sandwich plates is explained.
2. The influence of the rotational stiffness of the laser stake-welded T-joint on the buckling strength (Publication 1) and plate post-buckling stiffness (Publication 4) is presented.
3. Extensive physical experimental investigation is carried out to determine the influence of corrosion on the steel sandwich structure. Specimens are assessed after one and two years of submergence in the sea for the type of corrosion developed, rate of thickness reduction and the state of the laser welds (Publication 3).
4. Extensive physical experimental investigation is performed to validate numerical models for assessment of the ultimate strength of laser-welded web-core steel sandwich beams affected by general corrosion (Publication 3).
5. The influence of general corrosion on the plate stiffnesses is determined. This allows the calculation of the buckling strength of symmetrically corroded web-core steel sandwich plates using general laminate theories (Publication 4). It is demonstrated that the most sensitive stiffness component is the transverse shear stiffness in the direction opposite to the web plate.
6. It is validated that the equivalent single-layer laminate theory representation of the web-core sandwich plate gives an accurate prediction of plate buckling and post-buckling for global deformation (Publication 1, Publication 2).

1. Introduction

1.1 Background

Humankind is becoming increasingly aware that energy has to be used more efficiently to preserve the environment. One of the areas in focus is cargo shipping, which is responsible for the transportation of the majority of goods around the world. The International Maritime Organization (IMO) has set out regulations that require the reduction of greenhouse gas emissions in ships (IMO, 2011). Thus, the legislation for energy efficiency is becoming more demanding, which calls for changes in conventional ship design.

One possible way to increase the energy efficiency of a ship lies in reducing her structural weight, allowing a higher amount of cargo to be transported instead. Ships' structures are traditionally made of stiffened plates. Although the minimisation of their weight has received much attention in recent decades, advances in production technology have allowed the use of new structural concepts that allow higher weight savings. For example, a sandwich plate has a lower weight for the same bending stiffness of the traditional structure as a result of the material being positioned away from the neutral axis; see Figure 1. Further beneficial properties of sandwich plates are increased crashworthiness (Noor *et al.*, 1996; Valdevit *et al.*, 2004; Xue and Hutchinson, 2006; Valdevit *et al.*, 2006), space saving as a result of their low height, the possibility of system integration, etc.

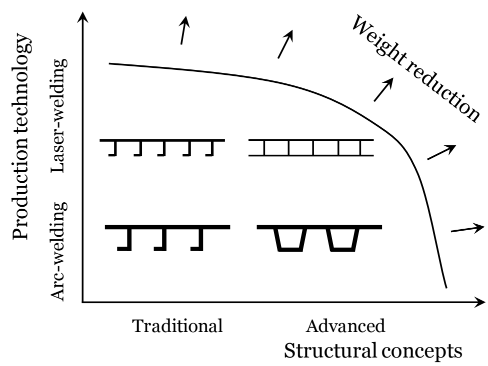

Figure 1. Advances in production technology allow the use of new structural concepts in ships.

Sandwich plates consist of a core enclosed by face plates. The core traditionally has a relatively low stiffness and carries the transverse shear loads. The faces have relatively high stiffness and carry the bending and in-plane loads. The core can possess various topologies: a web, a corrugation, a honeycomb, a cellular core, etc. (Allen, 1969). The core and faces can be selected from various materials: metals, composites, plastics, or organic materials. Ships are traditionally made from steel, and thus the selection of steel as the material for sandwich plates is convenient for welding them to the surrounding structure. Steel is easy to recycle and good against fire, but it is prone to corrosion.

The sandwich plates studied in this thesis are made from steel face and web plates. The web plates in the core extend in only one direction and are welded to the face plates by means of the laser welding technique (Teasdale, 1988; Roland and Reinert, 2000; Kujala and Roland, 2002; Bright and Smith, 2004) which enables thin plates (2-4 mm) to be used. The core of the sandwich plate can be filled with foam, which has a positive effect on the strength, damping, and corrosion (Romanoff and Kujala, 2001; Sandwich project, 2003; Kolsters and Zenkert, 2006a; Kolsters and Zenkert, 2006b). However, the focus of this thesis is empty sandwich plates since they are cheaper and easier to produce and the empty core can accommodate e.g. electrical wiring or piping. The web-core sandwich plate is stiffer in the direction of the webs, which is convenient for large ships where the longitudinal direction bears higher loads. The use of a sandwich plate as a part of the deck exposes the plate to ship girder loads as a result of the bending induced by waves, i.e. in-plane compression and tension; see Figure 2a. The use of web-core steel sandwich plates in ships is restricted by the limited understanding of their structural behaviour under such conditions and limited confidence in the efficiency of structural analysis methods.

In traditional structural elements of ships, such as stiffened and isotropic plates, the tensile load-shortening path is stable until the onset of material plasticity, i.e. yielding. Compression exhibits different, more dangerous behaviour; see Figure 2a. While the stress in the plate is still elastic, the plate can buckle, experiencing a sudden increase in the out-of-plane displacements. The value of the force at which this occurs is called the buckling strength. The increase in the compressive force continues in the post-buckling regime but the stiffness of the plate is reduced. Soon after the material starts to yield, the maximum force, called the ultimate strength, is attained.

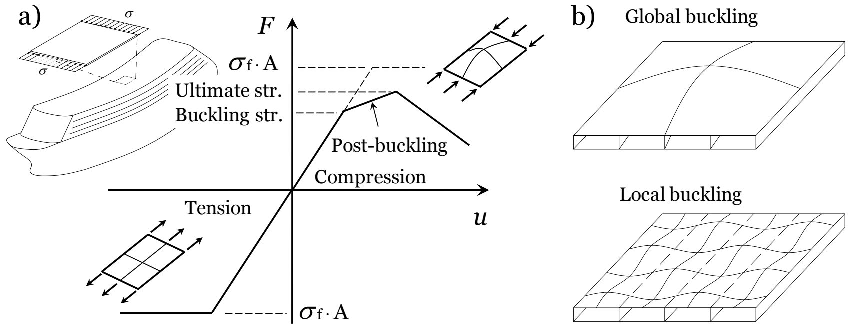

Figure 2. (a) Idealised behaviour of a plate in tension and compression loading; (b) Global and local buckling deformation. "σ_f" represents the yield strength of the material and "A" represents the cross-sectional area of the plate.

The plates are typically designed against buckling since it represents the start of a reduced compressive load-carrying capacity. Nonetheless, the post-buckling range can be reached by the plate being overloaded in an unexpected situation, for example in harsh sea conditions. Since this can endanger the safety of the ship, it is important to understand the post-buckling behaviour. Furthermore, ships operate in a corrosive marine environment, which can reduce the thickness of the plates. Thin plates are susceptible to buckling, and thus the influence of corrosion on the buckling and post-buckling of the sandwich plate has to be considered.

The buckling of web-core sandwich plates can occur in global or local mode; see Figure 2b (Aimmanee and Vinson, 2002; Vinson, 2005; Kolsters and Wennhage, 2009). Guided by the need to reduce weight and volume, ship structural design tends to produce slender sandwich plates in which the ratio of height to length and height to width is very low. This is because the plate is supported by the web frames and longitudinal girders, whose spacing is typically 3-7 meters, which is much larger than the height of the sandwich plate, e.g. h = 25-45 mm. This leads to the situation that the critical buckling mode of the plate is global, the form of deformation where the characteristic length is equal to the span of the plate and not the unit cell. The unit cell is the smallest repetitive volume of the plate, extending one web plate spacing, s, in y-direction, height being equal to that of the sandwich plate, h, and the length equal to infinitesimal length dx. Since there are no deformations from local buckling, the complexity of the problem is reduced. This could mean that simplified methods are suitable for the analysis, but this hypothesis requires investigation. Simplification can be performed using equivalent single-layer (ESL) laminate theory, which defines the sandwich plate in terms of homogenised stiffnesses; see Figure 3. This approach leads to a reduction in the computational efforts within finite element method (FEM) analysis in conceptual design. Furthermore, since stiffnesses have a physical meaning, it reveals the physical characteristics of the structure that control the compressive behaviour of the plate.

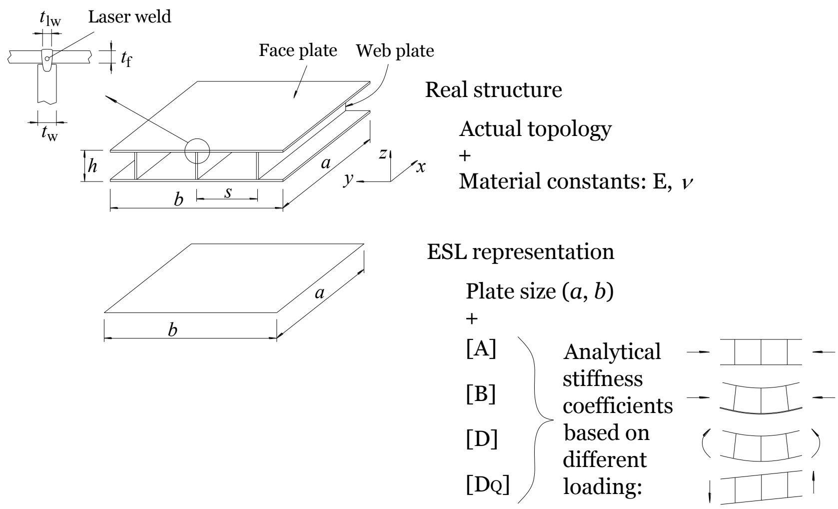

Figure 3. Differences in modelling a real sandwich structure in comparison to ESL approach.

1.2 State of the art

The buckling strength of an isotropic plate increases linearly with the bending stiffness of the plate (Bryan, 1891). In shear-deformable plates, shear stiffness plays an important role in addition to the bending stiffness (Allen, 1969, Noor, 1996, Reddy, 2004). When post-buckling is concerned, the in-plane stiffness also becomes important according to von Karman kinematics (Timoshenko and Gere, 1961). Therefore, understanding the in-plane, shear, and bending behaviour is important for sandwich plates under compression.

ESL theory relies on homogenised stiffnesses to reduce the number of problem unknowns. Libove and Bathdorf (1948) and Libove and Hubka (1951) assumed that the corrugated core sandwich plate follows the first-order shear deformation plate theory (FSDT; see Reddy, 2004). FSDT, in comparison to classical plate theory, includes the transverse shear strains that are assumed constant through the thickness of the sandwich plate. Since then, several modified stiffness formulations have been presented: for web-core sandwich plates see Chen *et al.* (1971), Lok *et al.* (1999), Kolsters and Zenkert (2002), and Kujala and Klanac (2002). However, in sandwich plates with a discrete core significant stress concentrations arise as a result of the shear-induced secondary bending of the constituent plates. The effect was presented for corrugated and Z-core sandwich plates in Wiernicki *et al.* (1991), Smith *et al.*

(1992), Fung *et al.* (1994), and Knox *et al.* (1998). Romanoff and Varsta (2006) presented a method to obtain the full state of stress (including the secondary bending stress) from the force resultants of the homogenised solution for the bending of web-core sandwich beams. The theory was extended to plates in Romanoff and Varsta (2007). The bending response was obtained for ESL plates in FEM relying on constant, homogenised stiffness properties. With the same approach, Engelstad *et al.* (1992) obtained the post-buckling response of a slender composite plate up to the point of first-fibre failure. This gives confidence concerning the applicability of ESL to the global buckling and post-buckling of web-core sandwich plates; however, it needs further study because of the material and topological differences between the plates.

The elastic response of sandwich plates using ESL requires the definition of homogenised stiffnesses. A web-core sandwich plate is specific in the way that the two transverse shear stiffnesses differ tremendously: the one perpendicular to the webs, D_{Qy}, is a few orders of magnitude smaller than that in the direction of the webs, D_{Qx}, because of the discrete arrangement of the core. The difference in the shear stiffness is further emphasised if the face and web plates are joined by means of laser welding, where the thickness of the weld is typically less than that of the web plate (Roland and Reinert, 2000). Consequently, the rotational stiffness of the T-joint is reduced, which increases the deflections in web-core sandwich beams (Romanoff *et al.*, 2007) and plates (Romanoff and Varsta, 2007). Similarly, for C- and Z-core sandwich plates Fung *et al.* (1996) and Fung and Tan (1998) showed that the shear stiffness can vary considerably, depending on the contact mechanism between the flanges of the core stiffeners and the face plates. For corrugated-core sandwich plates produced by adhesively bonding the faces with the core, Rahman and Abubakr (2004) and Haj-Ali *et al.* (2009) showed that the shear stiffness depends on the stiffness of the adhesive and also that it has an effect on the buckling strength of the sandwich plate. Romanoff *et al.* (2007) showed that the rotational stiffness of the T-joint is influenced by the local geometry: beyond the initial constant stiffness, the stiffness can increase as a result of contact between the plates, which increases the effective width of the laser weld. Therefore, a study on the influence of the stiffness of the T-joint on the buckling and post-buckling of the sandwich plate should be conducted.

Local buckling of face plates between the webs was studied in Kolsters and Zenkert (2006a, 2006b) for compression in the web plate direction and orthogonal to it, respectively. Although local buckling can be dominant in sandwich plates with thin faces, the typical span of girders in ships opens up the possibility of global buckling being the critical mode (Kolsters and Wennhage, 2009). For stiffened plates, the difference between the buckling strength and the ultimate strength is considered smaller in the case of global buckling (Hughes, 1983), which makes it a more dangerous mode in the way that the reserve in load-carrying capacity beyond the design point is reduced. Global buckling and post-buckling were studied for corrugated board plates, in Hahn *et al.* (1992) and Nordstrand (1995). Nordstrand (2004) presented an analytical and experimental investigation of their compressive behaviour until first-fibre failure. The plates exhibited first global and then local buckling, as in the study by Hahn *et al.* (1992). However, the difference between the two transverse shear stiffnesses in corrugated-core plates is much lower than in web-core plates. Furthermore, the structure does not include the deforming T-joint either. Therefore, the global buckling and post-buckling behaviour of web-core sandwich plates needs to be investigated.

Marine environments are recognised as being very corrosive for structural steel. Changes in the structure as a result of corrosion are known to affect all aspects of the plate response: the elastic part, buckling strength, and onset of plasticity. Corrosion is a complicated electrochemical process influenced by numerous factors (Melchers, 2008; Guedes Soares *et al.*, 2009). Significant reductions in the thickness of plates have been measured on ships in service (ABS, 2002; Paik *et al.*, 2003; Wang *et al.*, 2003), showing large deviations in reductions in thickness for ships of the same type and age (Guo *et al.*, 2008). Corrosion can occur throughout the ship, thus also in the upper decks as a result of green water, rain, and service water accumulation, all leading to high humidity in an aggressive marine atmosphere. There are numerous studies on the detrimental effect of corrosion on structural behaviour; a good overview can be found in the reports by ISSC (ISSC, 2009). The influence of corrosion on web-core sandwich beams has been investigated in the European Union Sandwich project (Sandwich consortium, 2003) and the investigation of Det Norske Veritas (DNV, 2003). However, these experiments were focused on observing corrosion wastage rates and the influence on stiffness only in the linear elastic regime. Therefore, the influence of corrosion on sandwich plate behaviour under in-plane compression needs to be investigated.

1.3 Scope of work

The present investigation focuses on the global buckling and post-buckling response of slender web-core steel sandwich plates; see Figure 4. The influence of the rotational stiffness of the T-joint on the buckling of the plate is explained in Publication 1. Initiation of the non-linear behaviour through geometric imperfection is studied in Publication 2. The effect of the magnitude of the imperfection on the post-buckling response is analysed. The shape of the initial imperfection is based on the available measurement data. In Sandwich project (Sandwich consortium, 2003), the imperfections in the 3-meter-long beams were measured in the direction of the web plates. The cross-sections of the beams were similar to those considered in this thesis. The measurements showed that the specimens are deformed mainly globally, with the node points at the ends of the beams. In the absence of plate measurements, global imperfection shape is considered in this thesis. Furthermore, Publication 2 explains the influence of the stiffnesses on the non-linear plate behaviour. The accuracy of prediction using the ESL theory is analysed in comparison to the FEM results where the actual topology is represented with shell elements. Experimental investigation of the influence of corrosion on the cross-sectional geometry, material properties and ultimate strength of web-core sandwich beams in three-point bending is performed (Publication 3). The credibility of the investigation requires experimental evidence as a result of the complexity of the corrosion process and the possible development of different types of corrosion. The corrosion condition is achieved in natural seawater instead of laboratory conditions since seawater is a complex mixture of chemical and biological processes which is very hard to replicate artificially (Little and Ray, 2002; Melchers, 2008). The accuracy of numerical tools for the prediction of the response is assessed in comparison to the experiments. The change in the post-buckling response as a result of corrosion is explained in terms of homogenised stiffnesses (Publication 4). The influence of general corrosion on the load carried and the stress state at the onset of plasticity is analysed.

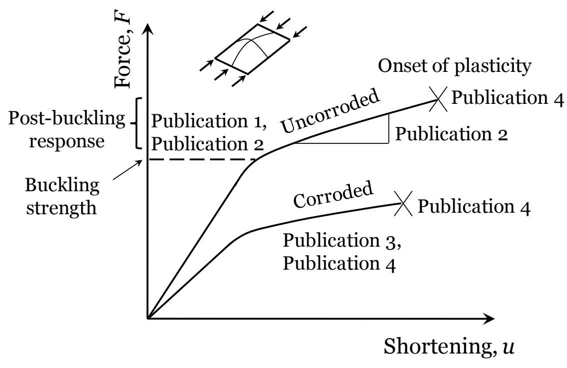

Figure 4. Outline of the investigation.

1.4 Limitations

1. In this thesis, the sandwich plates are studied under a uni-axial force since this is the primary loading direction in large thin-walled girders such as ships and bridges.
2. The study is performed on slender plates, which buckle globally, and high local stress concentrations do not occur until far into the post-buckling regime. Therefore, a linear elastic material curve for buckling and initial post-buckling is sufficient.
3. A symmetric sandwich plate (with respect to the neutral axes) is analysed since that cross-section is an industry standard and there is no membrane-bending coupling at the onset of loading. This allows a clear identification of a buckling strength.
4. The plate is modelled without the surrounding structure. This reduces the number of effects that can influence the nonlinear response of the plate.
5. The geometric nonlinear analysis is carried out using the global deformation shape as an initial imperfection, i.e. the initial deformation has a characteristic length equal to the span of the plate and not the unit cell. The measurements from web-core sandwich beams with similar cross-sectional proportions to those studied in this thesis showed that this is the typical imperfection shape.
6. For practical reasons, the exposure to sea water is limited to two years; the test specimens have a limited size and they are not exposed to mechanical loading while corroding.

2. Buckling strength

2.1 Influence of bending and shear stiffness

The buckling of the sandwich plate represents the starting point of reduced load-carrying capacity. The buckling strength of the ESL plate that follows the FSDT kinematics depends on the bending and transverse shear stiffnesses; see Robinson (1955) and Reddy (2004). The equation for the buckling strength is validated with 3D FEM model of the sandwich plate using shell elements in Publication 1. The buckling strength N_0 per unit width of a simply supported plate is:

$$N_0 = \frac{c_{33} + \left(\dfrac{\alpha^2}{D_{Qy}} + \dfrac{\beta^2}{D_{Qx}} \right) \cdot c_1}{\alpha^2 \cdot \left(1 + \dfrac{c_1}{D_{Qx} \cdot D_{Qy}} + \dfrac{c_2}{D_{Qx}} + \dfrac{c_3}{D_{Qy}} \right)}, \qquad (1)$$

where the coefficients are:

$$\begin{aligned}
&c_{33} = D_{11} \cdot \alpha^4 + 2 \; D_{12} + 2D_{33} \; \alpha^2 \beta^2 + D_{22} \beta^4; \\
&c_1 = c_2 \cdot c_3 - \; c_4 \;^2; \\
&c_2 = D_{11} \cdot \alpha^2 + D_{33} \cdot \beta^2; \\
&c_3 = D_{33} \cdot \alpha^2 + D_{22} \cdot \beta^2; \\
&c_4 = \; D_{12} + D_{33} \; \cdot \alpha \cdot \beta; \\
&\alpha = m \cdot \pi / a; \\
&\beta = n \cdot \pi / b.
\end{aligned} \qquad (2)$$

The variables m and n are selected in such a way as to make the buckling strength minimal. The most critical stiffness is the transverse shear stiffness opposite to the web plate direction, D_{Qy}. Since it is several orders of magnitude smaller than D_{Qx}, it severely limits the buckling strength. In comparison to long isotropic plate, buckling coefficient k is significantly lower than 4. Increasing D_{Qy} so that it has the same value as D_{Qx} doubles the buckling strength of the plate, whose cross-section is considered as an industry standard (Publication 2). Thus, it can be beneficial to design the sandwich plate with increased D_{Qy} because of the positive effect on the global buckling strength. The use of foam in the core (Kolsters and Zenkert, 2006a) or even having two-directional web plates (Xue and Hutchinson, 2006) will have such an effect. Naturally, there are additional design aspects that occur in these cases, such as added cost and weight. Therefore, an optimisation with a larger scope is required, which is out of the scope of this thesis.

A web-core sandwich plate can easily be designed to be symmetric with respect to its neutral axes, which means that the bending-extensional coupling (B-matrix) is a zero matrix. However, a stiffened plate is asymmetric with respect to its neutral axes, and thus the bending-extensional coupling is inherently built into the structure. As a consequence, the deflections develop as soon as any in-plane displacements are imposed on the stiffened plate. This significantly limits the buckling strength of a stiffened plate (Jelovica and Romanoff, 2013) and the buckling strength is in that case an approximation of the force at which the deflections suddenly increase.

2.2 Influence of T-joint rotational stiffness

The use of laser-welding technology to join web and face plates typically creates a weld that is thinner than the web plate. Therefore, the rotational stiffness of the T-joint is not infinite (as assumed by Chen *et al.*, 1971; Lok *et al.*, 1999; Aimmanee and Vinson, 2002; Kolsters and Zenkert, 2006a, 2006b; Kolsters and Wennhage, 2009) and the loading on the joint will change the 90° angle between the plates. The flexibility of the T-joint has a detrimental effect on D_{Qy} (Romanoff *et al.*, 2007). It causes a significant reduction of the buckling strength of the plate in comparison with the case of a rigid joint (Publication 1). However, the reduced weld stiffness does not affect the buckling strength of all the plates equally. The buckling strength reduces more in plates that have a large bending stiffness in addition to a significant reduction of D_{Qy}. This is because of the relative ratio of the transverse shear and bending stiffness in the buckling formula; see Eq. (1). In the case of sandwich plates with relatively small bending stiffness, the buckling strength is governed by c_{33} term in Eq. (1) and thus the changes in D_{Qy} do not have significant effect. On the other hand, in the case of plates with higher bending stiffness, the c_1 and c_3 coefficients increase and it results in higher influence of transverse shear stiffness.

When the length of the sandwich plate is greater than the width, the structure tends to buckle in a multiple half-waves in the longitudinal, loading direction. As the a/b ratio for a plate increases, so does the number of buckling half-waves in longitudinal direction, but their exact number depends also on the plate stiffnesses. Publication 1 demonstrates that the rotational stiffness of the T-joint is important to determine the exact plate aspect ratio where neighbouring buckling modes intersect (see Figure 5). The effect is recognised in sandwich plate theory to be related to the reduction of transverse shear stiffness of the plate (Allen, 1969). For corrugated cardboard plates, the same effect is noticed in the case of a reduced stiffness of the adhesive bond between the core and the faces (Rahman and Abubakr, 2004; Haj-Ali *et al.*, 2009).

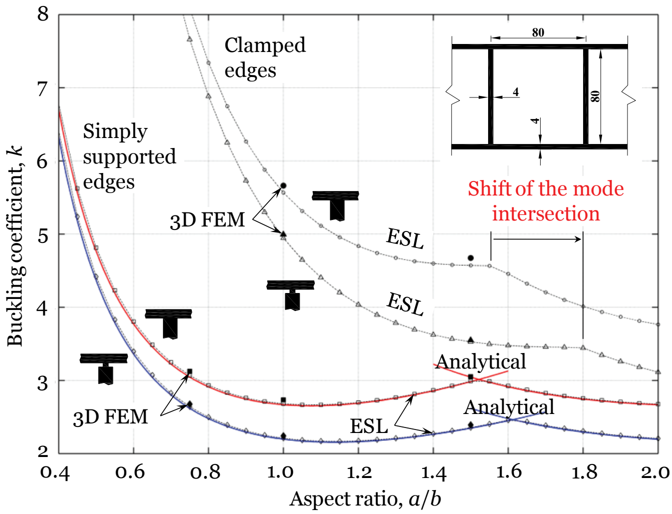

Figure 5. Influence of the rotational stiffness of the T-joint on the buckling strength of the sandwich plate (see Publication 1 for more details).

3. Post-buckling response

3.1 General

The sandwich plate carries an increasing force in the post-buckling range. The start of the global post-buckling domain depends, in addition to the buckling strength, on the shape and magnitude of the initial imperfection. Imperfections are always present in plates as a result of manufacturing, handling, etc. Global imperfection was measured in slender sandwich beams (Sandwich consortium, 2003), resulting in an increase in the deflections from the onset of loading; see Figure 6. Because of geometrical nonlinearity, the bifurcation buckling is an approximation of the point when a sudden increase in the deflections occurs (Publication 2). Comparison of the force carried for the same edge shortening reveals that the increase in the magnitude of the initial imperfection has negative effect on the force. This is because the load-carrying mechanism changes from membrane towards bending action. The effect of geometrical nonlinearity on compressive behaviour is in line with that of other types of plates (Jones, 2006).

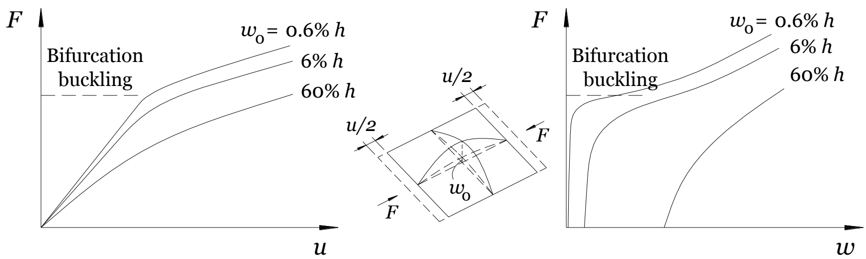

Figure 6. Influence of magnitude of imperfection on load-shortening and load-deflection behaviour of the sandwich plate (Publication 2).

The post-buckling stiffness (i.e. the slope of the load-shortening curve) is controlled by the in-plane stiffness (A-matrix) of the sandwich plate: the larger the cross-sectional area of the plate, the larger the post-buckling stiffness. The importance of in-plane stiffness for the post-buckling response was emphasised for other types of plates in e.g. Stein, 1983; Adali *et al.*, 1996; Paik *et al.*, 2001; Byklum *et al.*, 2004, Seresta *et al.*, 2005, Chen and Guedes Soares,

2007. In comparison to an isotropic plate with the same bending stiffness, a sandwich plate has a significantly lower post-buckling stiffness because of its lower cross-sectional area. Furthermore, a comparison with the stiffened plate with the same in-plane stiffness in both plate directions and undergoing global post-buckling shows that the structures have very similar post-buckling stiffness, which underlines the importance of in-plane stiffness in that range (Jelovica and Romanoff, 2013). Thus, a decrease in the post-buckling stiffness can be expected when the stiffened plate is replaced with a sandwich plate with a lower cross-sectional area.

The post-buckling curve obtained with the ESL approach shows an excellent correspondence with the shell element results of 3D structure (Publication 2). Thus, the extension of the use of ESL beyond the linear range for web-core sandwich plates (Romanoff and Varsta, 2007) is demonstrated. The validity of the approach in the same range was previously shown for composite plates (Engelstad *et al.*, 1992).

3.2 Onset of plasticity

The increase in the deflections and compressive force during the plate post-buckling leads to the material failure of mild steel according to the von Mises criterion. The onset of yielding occurs next to the unloaded edge, in the mid-span of the sandwich plate. The secondary bending stress in the y-direction is at its highest there (see Figure 7) and is greater than the membrane stress in the x-direction (Publication 4). The membrane stress increases towards the centre of the plate on the concave side; however, the maximum is still lower than that of the secondary bending at the edge of the plate. Kolsters and Wennhage (2009) considered the onset of plasticity in slender web-core steel sandwich plates using membrane stresses only, as did Paik *et al.* (2001) for stiffened plates. This non-conservative approach leads to a larger error as the amount of shear-induced secondary bending stress increases; see Romanoff and Varsta (2007). Neither was the secondary bending stress considered in the analytical failure prediction of corrugated sandwich plates during global post-buckling in Nordstrand (2004). It could be a contributory factor leading to the 6% lower ultimate strength in the experiments. The discrepancy was attributed to nonlinear material behaviour, although this was not measured in the experiments.

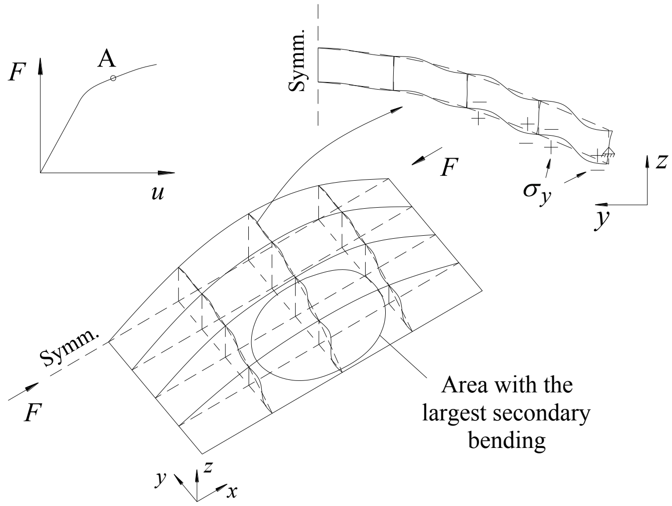

Figure 7. Shape of the face plates in an early post-buckling response.

3.3 Influence of local buckling

Considering that high-strength steel (σ_f > 355 MPa) is used as a material for slender web-core steel sandwich plates, the structure can experience local buckling prior to yielding. An increase in the compressive force on the sandwich plate leads to higher membrane stresses in the face and web plates. The distribution of the membrane stress changes so that the highest value occurs next to the unloaded edge of the plate; see Figure 8. Furthermore, the amplitude of the secondary bending deformation continues to increase, and thus the plates develop out-of-plane imperfections curved in both plate directions. Local imperfections are not included as initial imperfection shapes in this thesis. Under these circumstances, the face plate on the concave side, where the membrane stresses are higher, buckles locally, i.e. between the webs (Publication 2). However, local buckling occurs primarily in the centre of the face plate, although the membrane stress is higher at the edge; see Figure 8. The deformation as a result of secondary bending has made the face plate stiffer at the edge and postponed the local buckling. A noticeable increase in the force on the sandwich plate is required before the face plate buckles locally next to the unloaded edge. It also occurs on the convex side as a result of high membrane stress.

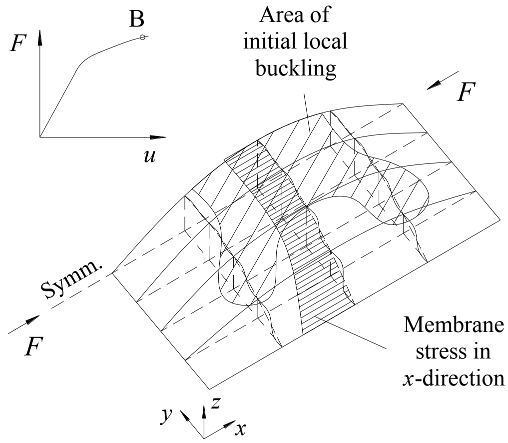

Figure 8. Deformation and membrane stress in the face plate leading to local buckling.

The difference in the compressive force between global and local buckling depends on the slenderness of the face plate, $\beta = b / t_{\mathrm{f}} \cdot \sqrt{\sigma_{\mathrm{f}} / E}$, the local buckling occurs sooner if the face plate is thinner (Publication 2). This is in line with the buckling of an isotropic plate, where more slender plates buckle at a lower stress. The post-buckling stiffness of the sandwich plate is reduced as a consequence of local buckling. The accuracy of the ESL approach decreases after that point since it cannot account for the local buckling. Homogenised stiffness properties have rendered the information on the local plate dimensions inaccessible. It is known from the literature that single-layer laminate theories are inadequate to represent the local effects (Reddy, 1989).

Local buckling occurs after global buckling in slender corrugated-core sandwich plates, as reported by Hahn (1991) and Nordstrand (2004). The studies merely observed this phenomenon; the conditions under which it occurred were not pursued further. Kolsters and Zenkert (2006a) presented a closed-form equation for local buckling in web-core sandwich structures, albeit for perfectly flat plates. Therefore, the approach is not applicable for the local buckling during global post-buckling. In this situation, complicated geometrical shapes influence the occurrence of local buckling.

4. Influence of corrosion on compressive behaviour

To determine the influence of corrosion on the mechanical properties of the sandwich structure, an experimental study on sandwich beam specimens that have corroded to different extents is performed (Publication 3); see Figure 9. The changes in the cross-sectional geometry, material properties and ultimate strength of the structure are determined in comparison to uncorroded specimens. The corroded state is achieved by immersion into the Baltic Sea for one- and two-year periods with water flowing in the direction of the web plates. It is observed that the plates are primarily affected by general corrosion. The average thickness reduction rates are similar to those obtained in other studies on submerged plates tested in different parts of the world (Melchers *et al.*, 2010). It is furthermore found that corrosion has negligible effect on the welds from those same specimens; see Aromaa *et al.* (2012). The specimens are tested in three-point bending where a significant reduction of the ultimate strength is observed for unprotected, corroded specimens: a cross-section that is considered an industry standard showed a reduction of their ultimate strength by 10% and 17% after one- and two-year exposure times, respectively. The implications for sandwich plates under compression are therefore required.

Figure 9. Sandwich beam specimens that have corroded to different extents.

The study of sandwich plates is conducted numerically since experiments involve substantial difficulties, e.g. producing the required force level and ensuring the desired boundary conditions. The justification for the use of numerical tools lies in their successful prediction of the ultimate strength of the corroded sandwich beams (Publication 3). Furthermore, the elastic properties of steel are observed not to change as a result of corrosion extent considered. Thus a study of slender corroded sandwich plates until the onset yielding can be conducted. Corrosion, however, changes the plastic behaviour of the material on the tensile specimen level: strain hardening starts as soon as the first yielding occurs and the failure strain is reduced. These observations on material behaviour are in line with those obtained in earlier numerical studies of tensile specimens (Ahmmad and Sumi, 2010; Islam and Sumi, 2011) and corroded bars (Almusallam, 2001).

For the corrosion extent considered in Publication 3, i.e. thickness reduction of about 0.5 mm, in practical cross-sections where the t_f/h_c ratio is small, the in-plane, bending and transverse shear stiffnesses depend linearly on the thickness of the face plate and the web plate (Publication 4). The transverse shear stiffness D_{Qy} shows the greatest decrease of all the stiffnesses as a result of the reduction of the thickness. The reduction of the stiffnesses doubles if, in addition to the outer faces, corrosion also occurs inside the sandwich plate. Figure 10 shows the reduction of load-carrying capacity in the sandwich plate from Publication 4, where the face plate thickness is initially 2.5 mm, webs are 4.0 mm, web plate spacing is 120 mm and the core height is 40 mm. In addition to the response of uncorroded plate, two cases are presented where the reduction of face plate thickness is 0.5 mm and 1.0 mm. It can be seen that the buckling strength and post-buckling stiffness of the sandwich plate are sensitive to general corrosion. The buckling strength is reduced linearly due to the change in stiffnesses. The reduction rate doubles in the event of corrosion being also in the core. Furthermore, the force at which the yielding occurs is reduced in the same rate as the buckling strength. Nonetheless, the physical experiments on sandwich beams showed that the ultimate strength can be preserved using different protection methods (Publication 3). However, the potential reduction rates for the ultimate strength suggest that special care should be directed towards proper corrosion protection for longer exposure periods. This is currently not reflected in the classification society guidelines for steel sandwich plates (Det Norske Veritas, 2003), which stipulate that corrosion protection should be performed as in traditional structures.

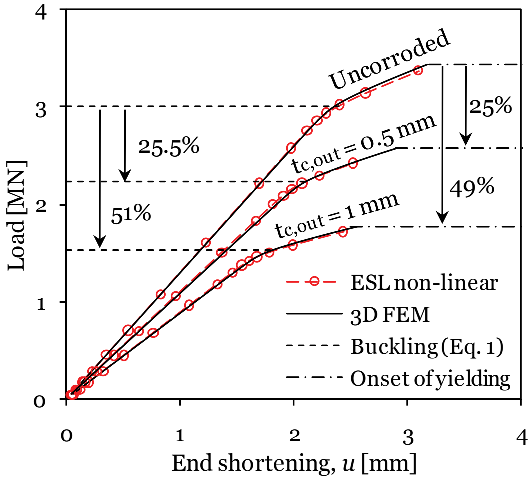

Figure 10. Reduction of load-carrying capacity because of the general corrosion (Reproduced from publication 4).

The rotational stiffness of the T-joint can increase as a result of the contact between the face and the web plate in the event of large rotations at the joint (Romanoff *et al.*, 2007). This occurs during the post-buckling response of the sandwich plate and results in the increase of the post-buckling stiffness (Publication 4). In the considered cases of corroded plates, however, the addition in stiffness does not occur because of the reduced transverse shear and bending stiffness coming from the thinner plates.

Corrosion changes the ratio between the stress components at the point of yielding. The secondary bending stress increases as the plates become thinner, becoming more important factor leading to material failure.

5. Conclusions and future work

This thesis investigated the buckling and post-buckling behaviour of slender web-core steel sandwich plates. The plates were assessed in uni-axial compression until the onset of plasticity. The first buckling mode of slender web-core sandwich plates is characterised with global deformation between the edge supports. It is known from the literature that the buckling strength causing the global deformation is defined through the bending and transverse shear stiffnesses of the sandwich plate. A particular feature of web-core sandwich plates is that the two transverse shear stiffnesses differ tremendously: the one perpendicular to the web-plate direction, D_{Qy}, is a few orders of magnitude smaller because of the discrete core. As seen in this thesis, this dramatically affects the buckling strength of the plate. Furthermore, the rigidity of the connection between the face and web plate has a significant effect on the transverse shear stiffness, D_{Qy}. The thickness of the laser weld being less than the thickness of the web plate makes the T-joint flexible. In turn, the transverse shear stiffness D_{Qy} decreases in comparison to a fully rigid joint. The buckling strength is reduced, especially in sandwich plates with a high bending stiffness, because of the relative ratio between the bending stiffness and the transverse shear stiffness. The reduction of the rotational stiffness of the T-joint can lead to the reduction of the number of buckling half-waves in a long plate.

The post-buckling stiffness (i.e. the slope of the load-shortening curve in post-buckling) is controlled by the in-plane stiffness of the sandwich plate: the larger the cross-sectional area of the plate, the larger the post-buckling stiffness. The shear-induced secondary bending stresses are very important for accurate estimation of the yielding. They arise as a result of the bending of the face and web plates on the scale of the unit-cell. The secondary bending of the face plates can also have an effect on the initiation of the local buckling. Deformation resulting from secondary bending can make the unloaded edge stiffer. Although the membrane stress can be higher there, the local buckling occurs further away where the secondary deformations are smaller, primarily in the centre of the face plate ($x=a/2$, $y=b/2$).

Corrosion significantly affects the buckling and post-buckling behaviour of a steel sandwich plate. For the initial thickness reduction of the plates, i.e. up to about 0.5 mm, in practical cross-sections where the t_f/h_c ratio is small, the in-plane, bending and transverse shear stiffnesses depend linearly on the thickness of the face plate and the web plate. The transverse shear stiffness D_{Qy} decreases the most of all the stiffnesses as a result of the reduction of the thickness. Because of the high reduction of D_{Qy}, the reduction rate of buckling strength is higher in sandwich plate than in stiffened plate (see Jelovica and Romanoff, 2014). The buckling strength reduces linearly, following the reduction of the stiffnesses. The reductions double if, in addition to the outer faces, corrosion also occurs inside the sandwich plate. The force at onset of yielding is reduced at the same rate as the buckling strength, which means that the safety margin between the design point of the structure and the onset of material failure remains unaffected. It was observed in this thesis through experiments that the ultimate strength of the web-core sandwich beams is reduced rapidly because of corrosion but, also, that it can be maintained using different protection methods. The findings highlight the importance of proper corrosion protection of the web-core sandwich plates in a marine environment.

The experiments showed local corrosion at the T-joint in some cases. This might reduce the stiffness of the T-joint and result in further deterioration of the load-carrying capability of the sandwich plate. However, this hypothesis requires experimental verification in the future. As this thesis indicates, the instrumentation for such experiments should be carefully planned since it is expected that the failure occurs at the plate edges rather than at the mid-plane which is typical for isotropic plates. In practice, despite the efforts for applying the high quality corrosion protection, the possibility of localized corrosion exists, especially considering the long periods these structures should be in use. Longer exposure periods of the plate to corrosive environment might lead to extensive local corrosion, i.e. crevice corrosion of the T-joint and/or pitting corrosion of the thin plates. These cases could lead to global failure and thus should be investigated in the future. Further work should also reveal the influence of the cross-sectional shape and the properties of the production process on the distribution, shape, and magnitude of initial imperfections in laser-welded web-core sandwich plates, especially for thinner face and web plates. This thesis considered global initial imperfections on the basis of measurements available in the literature on specimen sizes and cross-sections similar to those studied here.

The local buckling of face or web plates is not accounted for within the ESL method. In the future, the method could be extended to include the local buckling. This is important since it reduces the load-carrying capacity of the plate. Local buckling causes the change in the ABD-D_Q stiffness matrices and their non-linear values could be used instead. Similar approach was used in Byklum et al. (2004) for stiffened plates by semi-analytical method. Nonetheless, the ESL approach accurately predicts the load-shortening for global buckling and post-buckling. It allows a large reduction of the modelling and analysis time, which is especially interesting for the conceptual design since the same FEM mesh can be used for different cross-sections.

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It has become obvious that we have to improve the management over our resources. Steel sandwich plates are a step towards this goal. Besides the good mechanical properties, steel can be recycled and it is cheaper than many competing materials. Sandwich construction is more lightweight than conventional structures in e.g. ships, trailers or railway wagons, thus fuel can be saved in transportation. This thesis reveals some aspects of safety when using the sandwich plates – how they behave when approaching the failure. Corrosion is also considered since it is one of the most important types of damage in aging structures and can significantly influence their failure behaviour.

ISBN 978-952-60-5860-3
ISBN 978-952-60-5861-0 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934
ISSN 1799-4942 (pdf)

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