Degree project in Building Materials
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Hybrid bridge deck of timber and corrugated steel plates

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Hybrid bridge deck of timber and corrugated steel plates

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Master Thesis

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ABSTRACT

Over the years, hybrid structures composed of timber and steel have become a potential alternative to conventional solutions. Recently, corrugated steel plate (CSP) has become more and more popular in structures such as shear walls and roofs due to its favorable mechanical properties. However, all current research of bridge deck with CSPs has focused on the combination of CSPs and concrete, and there is a lack of studies on corresponding hybrid structures combining timber and CSP. The aim of this thesis is therefore to conduct an investigation of the possibilities to design a novel timber-CSP bridge deck.

The more specific objective of this thesis is to investigate the structural behavior and performance of timber-CSP hybrid bridge deck through laboratory tests and finite element simulations. The research focuses on the feasibility and reliability of the developed models and aims to provide insights for the design and analysis of this novel bridge deck. The feasibility and reliability of finite element modelling was validated by the laboratory tests. Afterwards, parametric studies of full-scale bridge decks were conducted to investigate the influence of the thicknesses of its timber boards and CSPs, and the positions of the load-bearing surface. The results reveal that an increase of thickness of the members significantly enhances the load-bearing capacity and stiffness of the bridge deck. Moreover, a simplified method is proposed to assist engineers in estimating the resistance of bridge deck against central load, including the bending moments and the maximum deflection. Finally, the requirements of the designed bridge deck were checked and discussed.

Keywords: Corrugated steel plate, timber, timber-CSP bridge deck, finite element simulation
SAMMANFATTNING (IN SWEDISH)

Under åren har hybrida strukturer bestående av trä och stål blivit ett bättre alternativ till konventionella lösningar. På senare tid har korrugerad stålplåt (CSP) blivit alltmer populär vid konstruktion av olika strukturer som skjuvväggar och tak på grund av dess fördelaktiga mekaniska egenskaper. Dock har all aktuell forskning om brobanor med CSP fokuserat på kombinationen av CSP och betong. Det finns inga befintliga studier om trä-CSP hybrida brobanor, så det är nödvändigt att genomföra en sådan undersökning av den nyskapande designade brobanan.


Nyckelord: Korrugerad stålplåt, trä, trä-CSP-brobana, fenita element-simulering
PREFACE

This master thesis has been carried out in the spring semester of 2023 at the Department of Civil and Architectural Engineering, Division of Building Materials at KTH Royal Institute of Technology.

First I would like to express my deep gratitude to my supervisor, professor Roberto Crocetti, for his exceptional guidance and assistance throughout the process of my thesis. I appreciated every advice he gave to me and his patience during my research. I am also deeply grateful to Professor Magnus Wålinder for his patient guidance and instruction, helping me learn more about timber materials.

Special thanks go to the PhD students Yue Wang and Tianxiang Wang as well as Viktor Brolund for their valuable support during my laboratory tests. Without their help, it wouldn’t have been possible to complete the tests. I also would like to express my sincere thanks to Charlotte Jaeger for her every help and discussion during the most challenging parts of my research.

I would like to thank the support from Jens Bergenudd and Ruoqi Wang about the software.

Lastly, I would deeply express my gratitude to my parents Guo Lu and Guifang Shi for their unfaltering support and encouragement during my master studies.

Muze Lu

Stockholm, June, 2023
## LIST OF ABREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>Young’s modulus (Pa)</td>
</tr>
<tr>
<td>$f_{m,k}$</td>
<td>Bending resistance parallel to grain</td>
</tr>
<tr>
<td>$f_{t,0,k}$</td>
<td>Tension resistance parallel to grain</td>
</tr>
<tr>
<td>$f_{c,0,k}$</td>
<td>Compression parallel to grain</td>
</tr>
<tr>
<td>$f_{c,90,k}$</td>
<td>Compression perpendicular to grain</td>
</tr>
<tr>
<td>$f_{v,k}$</td>
<td>Shear</td>
</tr>
<tr>
<td>$E_{0,\text{mean}}$</td>
<td>Elastic modulus parallel to grain</td>
</tr>
<tr>
<td>$E_{90,\text{mean}}$</td>
<td>Elastic modulus perpendicular to grain</td>
</tr>
<tr>
<td>$G_{\text{mean}}$</td>
<td>Shear modulus</td>
</tr>
<tr>
<td>$\rho_{\text{mean}}$</td>
<td>Density</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness</td>
</tr>
<tr>
<td>$f_{ty}$</td>
<td>Strength</td>
</tr>
<tr>
<td>$q_{\text{self}}$</td>
<td>Own weight</td>
</tr>
<tr>
<td>$M_d$</td>
<td>Moment resistance</td>
</tr>
<tr>
<td>$M_{Ed}$</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>$M_P$</td>
<td>Bending moment under external concentrated load</td>
</tr>
<tr>
<td>$I_{\text{eff}}$</td>
<td>Effective moment of inertia</td>
</tr>
<tr>
<td>$P$</td>
<td>External concentrated load</td>
</tr>
<tr>
<td>$L$</td>
<td>Span length of bridge deck</td>
</tr>
<tr>
<td>$\sigma_P$</td>
<td>Internal stress of the CSP subjected by concentrated load</td>
</tr>
<tr>
<td>$\sigma_{\text{FEM}}$</td>
<td>Internal stress of the CSP obtained from simulation results</td>
</tr>
<tr>
<td>$W_{\text{fict}}$</td>
<td>Fictious section inertia of the CSP</td>
</tr>
<tr>
<td>$z_{\text{edge, max}}$</td>
<td>Distance from the neutral axis to the outer edge of the cross-section</td>
</tr>
<tr>
<td>$b$</td>
<td>Width of one corrugated folds</td>
</tr>
<tr>
<td>$n$</td>
<td>The number of corrugated folds that are objected by the concentrated load</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the CSP</td>
</tr>
<tr>
<td>$\delta_P$</td>
<td>Maximum deflection of simply supported beam</td>
</tr>
<tr>
<td>$\delta_{\text{FEM}}$</td>
<td>Maximum deflection obtained from simulation results</td>
</tr>
<tr>
<td>$q_c$</td>
<td>Crowd load</td>
</tr>
<tr>
<td>$q_{\text{Ed}}$</td>
<td>Designed uniformed load</td>
</tr>
<tr>
<td>$u_{\text{max}}$</td>
<td>Maximum deflection of bridge deck</td>
</tr>
<tr>
<td>CSP</td>
<td>Corrugated Steel Plate</td>
</tr>
<tr>
<td>ETDW</td>
<td>Effective Transverse Distribution Width</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>ULS</td>
<td>Ultimate limit state</td>
</tr>
<tr>
<td>SLS</td>
<td>Serviceability limit state</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer</td>
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1 INTRODUCTION

1.1 Background

Throughout the history of mankind, wood has been a material of immense potential because of its affordability and vast availability as a raw resource. The structural capabilities and aesthetic value of timber have made it a desirable material. From many years ago, timber had been used for shelters and tools and now it is used for construction, furniture, art-related stuff, etc. As a construction material, timber is used in structures such as timber framed buildings, timber bridges and some specific tools. When properly designed with regular maintenance, timber structures have the potential to offer a longer service life compared to alternative materials. Engineered wood products (EWP), including glued-laminated timber, stress-laminated decks, and preservative treated timber, etc., expand the visions for engineering design professionals working with wood.

Timber bridge construction has a long-standing history, primarily used for transportation over waterways. In the 19th century, plenty of timber bridges were designed all over the world. M.A. Ritter (1990) published all relevant popular timber structure designs and the maintenance of them. Wood has many advantages for bridge constructions, including being a renewable resource, contributing to global warming mitigation, and having a high strength-to-weight ratio. Timber bridge has a positive effect on mitigating global warming as the wood material can store a significant amount of greenhouse gases, such as CO2, with one kilogram of timber capable of storing 1.7 kilograms of CO2 during construction (K.A. Malo 2022). Since the 20th century, timber has become a favorable material for modern bridge construction due to its low weight and shorter construction periods (Ekholm et al. 2013).

Over the years, hybrid structures consisting of timber and steel have become a valid alternative to conventional solutions. Timber-steel hybrid structures demonstrate excellent seismic performance due to steel’s ductility behavior and timber’s high strength-to-weight ratio. Timber-steel hybrid beams also have a significant increase in stiffness, strength and ductility (Wang, T. 2021) and Wang et al. also investigate multiple timber connections with dowel-type fasteners. Recently, Corrugated Steel Plate (CSP) is more and more popular in the construction of different structures such as shear walls and roofs due to its several advantages, e.g., great strength of steel, low construction cost, short installation time, less maintenance, better durability and long service time. The utilization of CSPs is able to increase the stiffness of floors and bridge deck. A comparison of corrugated and flat paper is shown as Figure 1.1. Marsel et al. studied the load-bearing capacity of cold-formed sinusoidal corrugated steel sheets and its design methods. Some studies have been conducted in the hybrid flooring system consisting of CSP and concrete, which utilize concrete in compression and CSP in tension. John (2020) investigates the structural response of newly designed corrugated steel deck used in concrete slab and the results demonstrated significant resistance to bending and buckling. Guo Min et al. (2016) used the finite element software ABAQUS to develop a model of a corrugated steel and concrete composite bridge deck. The simulations conducted demonstrated that the corrugated steel plates significantly increase the capacity of load bearing and the stiffness of the bridge deck. Corrugated steel plates can be easily assembled with bolt and other connections and detailed assembly instructions can be obtained from the manufacturer.
However, current research efforts has primarily focused on the performance of hybrid bridge decks composed of concrete and steel. In the case of timber bridges, the structural framework of them typically comprises the deck, main support members and railings (K.C.K. Cheung 2001) and timber deck bears the weight and load from traffic, serving as roadways on timber bridges. Timber deck faces similar risks of bending resistance as concrete deck due to direct loads from vehicles, pedestrians and even snow particularly in northern regions. The risk of timber and connection failures, as well as unacceptable deflection in the middle of the bridge deck exists. Since there are no existing studies on timber-CSP hybrid bridge deck, it is necessary to conduct an investigation into such newly designed bridge deck.

In modern construction, there is an increasing interest in performance of bridge when subjected to various loads such as vehicles and pedestrians. Possible concentrated loads are a wheel of vehicles, structural and mechanical components. Degtyarev (2020) developed finite elements models and conducted a comprehensive parametric study on CSPs subjected to concentrated loads. The study includes analysing the effective transverse distribution width (ETDW) which represents the width of the deck that effectively resists the applied loads. Biegus et al. (2010) presents an equivalent concentrated load factors for each individual corrugated fold used to analyze load resistance and stiffness of corrugated sheets. Therefore, the development of a simplified method to determine the effective width for hybrid bridge deck consisting of CSPs and timber boards is necessary and beneficial for practicing engineers involved in the design of such deck configurations.

1.2 Purpose

In this thesis, a novel bridge deck consisting of corrugated steel plate and timber boards was designed and the stress distribution and maximum deflection of the deck in ultimate limit state (ULS) and serviceability limit state (SLS) was analyzed. This thesis also describes the development of finite elements models of laboratory tests and the timber-CSP hybrid bridge deck subjected to concentrated loads. The developed finite elements model was used for a parametric study for the designed bridge deck under concentrated loads. A simplified method to estimate the resistance of the timber-CSP bridge deck loaded at the center is provided. Figure 1.2 presents an overview of the designed timber-CSP bridge deck. The corrugated steel plates were placed under timber boards.
1.3 **Limitations**

During the research, the following limitations apply:

- The investigation of ultimate limit state analysis and the simplified method will focus on concentrated load at the center.
- The material is modelled as a homogeneous material, disregarding any imperfections or initial movement of the wood and steel plate.
- Buckling will not be visualized in modelling results and the non-linear analysis will focus on deflection and stress distribution of bridge deck.
- Wind load is not considered in SLS analysis.

1.4 **Method**

A theory study was conducted first to gain knowledge about the properties of designing timber and corrugated steel plate. Properties of CSP need to be checked in product information sheets from companies and manufacturers.

In order to ensure that the designed timber-CSP bridge deck fulfils the functional requirements, two main methods, laboratory experiments and simulation analysis, are proposed. The laboratory experiments need to control all background factors such as boundary conditions, thickness of timber boards and CSPs. The central deflection is measured by sensors and a diagram with load and deflection relationship can be obtained to analyze the performance of test specimens of the bridge deck. The test deck utilized in laboratory experiments has a smaller size compared to the real deck.

ABAQUS is used as finite element analysis software in the simulation study. A model of laboratory tests is built in ABAQUS with some assumptions. It is not necessary to model every detail of the test deck because this research only focus on stress distribution and central deflection of it. Through the manipulation, different configurations such as connections between timber boards and CSP are set and the deformation of CSP is observed. A comparison is made between the load-deflection plots obtained from the modelling results and the laboratory test results. This comparison aims to validate the credibility and accuracy of the finite element (FE) models.

The bridge deck with real dimensions is modelled and an extensive parametric study is conducted under concentrated load. Load on supports is also tested in FE models. By analysing the results plots and employing simple calculations, it becomes possible to propose a simplified method for estimating the effective number of folds taking the entire load.
1.5 Outlines

Chapter 2 introduces the properties of materials which are used in laboratory tests and simulation analysis.
Chapter 3 focuses on three laboratory tests and the results are presented in the form of load-deflection plots.
Chapter 4 describes the tests modelling using ABAQUS and the comparison between simulation results and test results.
Chapter 5 describes the designed timber-CSP bridge deck modelling using ABAQUS and a parametric study of different thickness. The chapter also presents the performance of CSP when loading on supports. A simplified method of estimating the resistance of bridge deck is proposed in this chapter. And the SLS analysis of the designing bridge deck is presented to validate that the timber-CSP bridge deck meets all the safety requirements.
Chapter 6 makes a conclusion and discussion on all the obtained results.
Chapter 7 includes recommendations for potential future research work.
The main materials for this thesis are timber, corrugated steel plates and the screw connections.

### 2.1 Timber

The class of timber boards of laboratory tests and simulations is C24. The material properties are given in Table 2.1, acquired from SS-EN 338:2016.

<table>
<thead>
<tr>
<th>Property</th>
<th>C24</th>
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<tbody>
<tr>
<td>Bending parallel to grain $f_{m,k}$</td>
<td>24</td>
</tr>
<tr>
<td>Tension parallel to grain $f_{t,0,k}$</td>
<td>14.5</td>
</tr>
<tr>
<td>Tension perpendicular to grain $f_{t,90,k}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Compression parallel to grain $f_{c,0,k}$</td>
<td>21</td>
</tr>
<tr>
<td>Compression perpendicular to grain $f_{c,90,k}$</td>
<td>2.5</td>
</tr>
<tr>
<td>Shear $f_{s,k}$</td>
<td>4.0</td>
</tr>
<tr>
<td>Elastic modulus parallel to grain $E_{0,mean}$</td>
<td>11000</td>
</tr>
<tr>
<td>Elastic modulus perpendicular to grain $E_{90,mean}$</td>
<td>370</td>
</tr>
<tr>
<td>Shear modulus $G_{mean}$</td>
<td>690</td>
</tr>
<tr>
<td>Density $\rho_{mean}$</td>
<td>420</td>
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</table>

### 2.2 Corrugated Steel Plate

The class of CSPs used in laboratory tests is LLP20 from Lindab Coverline™ (2023). And the class of CSPs in designed timber-CSP bridge deck is TP200 from ArcelorMittal Construction. The properties can be obtained from product information sheets which are presented in Table 2.2. In the provided table, the values of moment of inertia are based on the wide flange pressure affected. The comparison between narrow flange pressure affected and wide flange pressure affected is shown as Figure 2.1. Due to the bending moment directions depicted in Figure 2.2, the wide flange of the CSPs takes compression, leading to local buckling. Therefore, the effective moment of inertia $I_{eff}$ should be used as the cross-section of the CSPs under compression should be reduced, as shown in Figure 2.3. The requirements for screw connections are also outlined in Table 2.2, and their dimensions are measured as 4.8 mm in diameter and 35 mm in length, as shown in Figure 2.4.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>LLP20</th>
<th>TP200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Strength $f_{ty}$</td>
<td>N/mm²</td>
<td>250</td>
<td>420</td>
</tr>
<tr>
<td>Own weight $q_{self}$</td>
<td>kN/m²</td>
<td>0.05</td>
<td>0.211</td>
</tr>
<tr>
<td>Moment resistance $M_d$</td>
<td>kN/m²</td>
<td>0.57</td>
<td>45.94</td>
</tr>
<tr>
<td>Moment of inertia $I_{eff}$</td>
<td>mm⁴/mm</td>
<td>24.62</td>
<td>13873</td>
</tr>
<tr>
<td>Screws connection</td>
<td>pcs/m²</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

End layer 2 pcs screws in each profile base.
Figure 2.1. Narrow flange pressure affected and Wide flange pressure affected

Figure 2.2. Bending moments when wide flange pressure affected

Figure 2.3. Effective cross section due to local buckling

Figure 2.4. Screws (4.8mm*35mm) used in experiment
The laboratory experiments were conducted in three separate tests, with each test utilizing one single corrugated steel plate. The tests were performed as follows:

- **Test 1**: The CSP was tested without any timber boards.
- **Test 2**: The CSP was tested with timber boards, but without any connections between them.
- **Test 3**: The CSP was tested with fully connected timber boards.

From the overview of tests, it can be seen that Test 3 is more similar to the real bridge deck. To provide boundary limitations for the test decks, a support frame was constructed. Figure 3.1 describes the support frame created using SketchUp software. The specific details and design of support frame can be visualized and understood through the model in SketchUp. In each test, screws were employed with dimensions of 4.8 mm * 35 mm. These screws were utilized to connect and fix various components within the test setup.

![Image of support frame](image)

**Figure 3.1. Overview of support frame in tests, made using SketchUp software**

### 3.1 Plate and boards

For the laboratory test, LLP20 was selected as the specific configuration. Due to space limitations in the laboratory, the dimensions of the test deck were reduced to 0.63 m * 1 m. The cross-section and a overview of the corrugated steel plate is presented in Figure 3.2 and 3.3. Timber boards placed on the CSP have dimensions of 0.48 m in width, 0.63 m in length, and a thickness of 12 mm, as shown in Figure 3.4 and 3.5. These configurations were chosen for the experimental setup. Figure 3.6 provides an overview of the layout of the test deck, presenting the arrangement and positioning of timber boards and CSP within the setup.
Figure 3.2. Cross-section of test plate

Figure 3.3. Overview of test plate

Figure 3.4. Cross-section of test timber board

Figure 3.5. Overview of timber board
3.2 Loads

To assess the performance of the test deck, two types of concentrated loads were employed in different tests due to the reduced dimensions of the test deck, the dimensions of which is shown in Figure 3.7. For the CSP without timber boards (Test 1), a square area of load was applied. This configuration allows for better visualization of the buckling deformation of the steel plate. On the other hand, for the test involving the CSP with timber boards (Test 2 and 3), a circular area of load was utilized. Figure 3.8 illustrates the placement of the two concentrated loads on the test deck.

Figure 3.6. Arrangement and positioning of timber boards and CSP

Figure 3.7. Two types of concentrated load in test
3.3 Measurement

To analyze the performance of different tests, the maximum deflection at the center of the deck was measured. The Linear Variable Differential Transformer (LVDT) was used as deflection measurement device in this thesis. Two LVDTs were positioned beneath the CSP to measure the deflection and the supports were fixed on the MTS (Material Testing System) machine which is used to apply loads. This setup ensured that the movement of the MTS machine did not affect the measurement results. The test results were derived by averaging the data obtained from these two LVDTs, providing an accurate representation of the maximum deflection of the test deck.
3.4 Test 1

Two specimens were prepared and subjected to loading until the steel plate reached the yield state. One of the specimens was connected with support frame by screws on all four sides of the steel plate, while the other was fastened only on two shorter sides. This configuration is illustrated in Figure 3.10, 3.11 and 3.12. Figure 3.12 illustrates the sides without screws and lacking support, which shows the difference (marked as a red rectangle) between these sides in both specimens as compared to Figure 3.11. The load-bearing position is indicated in Figure 3.13. It is worth to note that Test 1 was conducted within the elastic range of the steel plate.

Figure 3.10. Specimen screwed on all four sides (left) and on two sides (right)

Figure 3.11. One side of specimen screwed on all four sides

Figure 3.12. One side of specimen screwed on two sides
3.5 Test 2

Two specimens of corrugated steel plates were prepared using the same configurations as Test 1. One of the specimen was connected with support frame by screws on all four sides, while the other one was screwed on two short sides only. Additionally, timber boards were placed on the CSP without any connections. Because most of timber boards were placed on the CSP without any interaction with loads or supports, they can be removed without any influence to test results. Therefore, only two timber boards under the applied load were placed on the CSP. The arrangement is shown as Figure 3.14 and 3.15. Both specimens exhibited a similar failure mode, which is depicted in Figure 3.16. The failure mode provides insights into the specific behavior and structural response observed in the test deck, from which the buckling at the wide flange can be visualized clearly.

Figure 3.14. Comparison of specimen screwed on two sides (left) and on all four sides (right)

Figure 3.15. Two specimens under loading
3.6 Test 3

In this test, a total of 20 timber boards were screwed to a single steel plate. The entire test deck including both timber boards and CSP was screwed to the support frame on all four sides, as shown in Figure 3.17 and 3.18. This configuration mirrors the design of the real bridge deck. The failure mode observed in Test 3, as shown in Figure 3.19 and 3.20, revealed the presence of local buckling near the load-bearing location, which provided notable observations regarding the behavior and response of the CSP under the applied load.
Figure 3.18. Location of screws between timber boards and CSP

Figure 3.19. The deformation of timber boards under the applied load
3.7 Results

The relationship of load-deflection at the center of the test deck is shown in Figure 3.21. The diagram illustrates that there is minimal difference between two sides screwed specimen and four sides screwed specimen in terms of the observed deflection. During Test 3, the data named Test 3_duplicated was conducted due to a software crash in the MTS machine when the load reached approximately 20 kN. Despite this incident, the diagram show that such a crash occurred did not affect the results because the test deck is still in the elastic range.

In Test 2 and 3, some drops in the load-deflection line can be observed, which can be attributed to the failure of timber boards. Despite these drops, the overall trend still indicates that the inclusion of timber boards considerably enhances the stiffness and resistance of the corrugated steel plate. This result highlights the significant contribution of timber boards to the overall structural performance and load-bearing capacity of a timber-CSP bridge deck.
Figure 3.21. Relationship between load and deflection in tests
In this chapter, a finite element shell model is developed to simulate the tests conducted and described in Chapter 3. The shell model is employed to validate its usability and sufficiency, in order to replicate and analyze the structural behavior and response of the test deck under various loading conditions. The FE models allows for further detailed investigations on the performance of the designed timber-CSP bridge deck.

### 4.1 Materials

In Chapter 2, the properties of both timber and corrugated steel plates are described. The CSP is composed of steel and is characterized by an elastic modulus of $2.03 \times 10^5$ MPa, a Poisson’s ratio of 0.3, and a yield stress of 250 MPa. A shell model is created to describe the non-linear relationship between applied load and central deflection. An orthotropic material is assigned to timber boards, taking into account its specific orientation, which is shown in Figure 4.1. This means the material properties of the timber such as stiffness and strength are defined differently along different directions, reflecting the inherent characteristics of an orthotropic material. The orientation setup ensures that timber boards in the model behave realistically and respond appropriately to the applied loads and boundary conditions.

![Figure 4.1. Orientation setup of timber boards](image)

The dimensions of the steel plates and timber boards used in the FE models are the same as those of the test deck described in Chapter 3. Same dimensions are essential for accurately representing the physical characteristics and behavior of the bridge deck in the FE analysis.

### 4.2 Loads and Boundary Conditions

To simulate the experimental conditions accurately, a rectangular frame is created in the finite element model. In the simply supported frame configuration, one short edge’s displacements in the x, y, and z directions are set to zero, effectively fixing it in place. Meanwhile, the other short edge is allowed to move freely in the z direction but its displacements in the x and y directions are also set to zero. Such same setup is applied to both long edges but one of the long edges only has x directions set free. And all rotational degrees of freedom are set free.

The loads applied in the models are set correctly to match the different tests. For Test 1, the load is applied on a square surface with dimensions of 50 mm * 50 mm. For Test 2 and 3, the load is applied on a circular surface with a diameter of 50 mm. The configuration of the frame and the load application is illustrated in Figure 4.2 and 4.3, where the rectangle represents the frame structure.
4.3 Interaction

In the three tests, the CSP is constrained to the rectangular frame, resulting in simply supported conditions on the constrained sides of the CSP. To simulate the test deck, the load surface and the center surface of the CSP are assumed to remain fixed, and therefore, they are set as constrained in the models. Similarly, the surfaces that were connected with screws in the laboratory tests are also assumed to be constrained in the models, providing a simplified representation of their structural behavior.

The contact surface between timber boards and upper surfaces of the CSP is modelled as ‘Normal behavior’, which allows for the transmission of pressure between the surfaces. Additionally, ‘Tangential Behavior’ is also applied to the contact surfaces, with a friction coefficient set to 0.3 to account for the tangential friction forces between timber boards and steel plate.
4.4 Element Mesh

To facilitate accurate calculation of results, the approximately element size of the corrugated steel plate is set to 20 mm, while the element size for timber boards is set to 36 mm. The element mesh of the tests is illustrated in Figure 4.4, providing a visual representation of how the elements are distributed and connected throughout the model.

![Figure 4.4. Element mesh of the three tests](image)

4.5 Results and Conclusions

4.5.1 Test 1

The plastic behavior of the materials is simulated using ABAQUS, as shown in Figure 4.5 and 4.6, which illustrate the plastic deformation observed in the simulation model. The ultimate limit load is approximately 0.3 to 0.4 kN, which is the maximum load that the system can take before yielding. From the diagrams it can be seen that the simulation results match the test results well.

![Figure 4.5. Comparison between simulation model and laboratory test, two sides screwed](image)
Furthermore, the comparison between two simulation models, as shown in Figure 4.7, reveals that there is minimal differences when employing two different boundary conditions. The analysis indicates that the choice of the number of edges screwed has limited influence on the overall structural behavior of test deck.

![Figure 4.6. Comparison between simulation model and laboratory test, all four sides screwed](image)

4.5.2 Test 2

It’s clearly to see the similarities between the simulation results and laboratory test results in Figure 4.8 and 4.9. These figures demonstrate the close agreement between those two load-deflection plots, indicating the accuracy and reliability of the simulation model in Test 2. Moreover, Figure 4.10 illustrates that the choice of different boundary conditions also has minimal influence on the deflection results in Test 2. This observation further supports the robustness of the simulation model and suggests that the two boundary conditions have similar impact on the overall structural behavior of test deck.

![Figure 4.7. Comparison between two simulation models with different boundary conditions](image)
Figure 4.8. Comparison between simulation model and laboratory test, all four sides screwed

Figure 4.9. Comparison between simulation model and laboratory test, two sides screwed
4.5.3 Test 3

The simulation results, as depicted in Figure 4.11, align closely with the laboratory test results. This strong agreement between the simulated and experimental data validates the accuracy and reliability of the FE shell model with the same setup to the designed real deck.

Figure 4.10. Comparison between two simulation models with different boundary conditions

Figure 4.11. Comparison between simulation model and laboratory test, with full boards

The comparison of the three tests further confirms the suitability of the FE shell models for parameter studies and design procedures. The ability to accurately capture the structural behavior and response of timber-CSP bridge deck in different loading combinations makes the models a valuable tool for conducting further investigations and research.
5.1 Modelling in Ultimate Limit State

The configuration and settings of the model in Chapter 4 remain unchanged. In this chapter, a different type of corrugated steel plate, TP200, is used for the real bridge deck design. The properties of TP200 CSP are mentioned in Chapter 2. The steel plate for the real bridge deck has a span length of 4 meters and a width of 2.615 meters. The cross-section of the steel plate is shown in Figure 5.1 according to product information sheet from ArcelorMittal Construction, providing a visual representation of its geometry and dimensions. The designed value of thickness of the CSP is 1.5 mm and that of timber boards is 45mm.

Figure 5.1. Cross-section of TP200 used in modelling from ArcelorMittal Construction

For the simulation in this chapter, the area of the central load is assumed to be equivalent to the contact area of a single wheel with a side length of 0.2 meters according to Eurocode BS-EN 1991-2:2003. This type of load is used for parametric study in ULS analysis in order to investigate the performance of designed deck with different thickness of timber boards and CSP. The load area is illustrated in the simulation model as Figure 5.2.

Figure 5.2. Load and boundary conditions of designed bridge deck
5.2 Parametric Study of Different Thickness

In the simulation, different thickness of timber boards and CSPs are analysed. The results for CSP, with thicknesses of 1.5 mm and 1 mm, connected to timber boards of various thicknesses (20 mm, 40 mm, 60 mm, 80 mm, 90 mm) are presented in Figure 5.3 and 5.4. It can be seen that when utilizing typical parameters in real engineering projects, such as 45mm thick timber boards and a maximum acceptable deflection of 10mm, the load capacity varies from 30kN to 20kN. This variation is depicted as a bold red line in Figures 5.3 and 5.4.

Figure 5.3. Comparison between different thickness of timber boards, 1.5mm CSP

Figure 5.4. Comparison between different thickness of timber boards, 1mm CSP
The figures clearly indicate that increasing the thickness of timber boards from 20 mm to 90 mm results in a significant enhancement in load resistance and stiffness of bridge deck. The load resistance is observed to increase by approximately 1.4 – 1.5 times when comparing the different thicknesses of timber boards. These findings indicate that thicker timber boards contribute to the load-bearing capacity and overall strength of the timber-CSP bridge deck, resulting in improved performance and resistance to applied loads.

When comparing the load resistance between CSP with different thicknesses, it is evident that the CSP with a thickness of 1.5 mm exhibits a larger load resistance compared to the CSP with a thickness of 1 mm. 1.5 mm thick CSP has approximately 1.5 times load resistance higher than 1 mm thick CSP. The comparison between different thicknesses of CSPs connected with timber boards of various thicknesses is illustrated in Figure 5.5, 5.6, and 5.7.

![Figure 5.5](image1.png)  
**Figure 5.5.** Comparison between different thicknesses of CSP, with timber boards of 20 mm and 40 mm thickness

![Figure 5.6](image2.png)  
**Figure 5.6.** Comparison between different thicknesses of CSP, with timber boards of 60 mm and 80 mm thickness
5.3 Parametric Study of Loading on Supports

The location of the applied load are shown in Figure 5.8. The thickness of timber boards is 45 mm and the thickness of the CSP is 1.5 mm. The results presented in Figure 5.9, 5.10, 5.11 and 5.12 demonstrate that timber boards do not contribute to the load resistance if the external load is applied directly to the CSP, leading to local yielding of steel, because in Figure 5.12, the change curves of the load on the CSP without timber boards and the load on the CSP with timber boards exhibit a high level of similarity, indicating that there is minimal difference between them. When the load is applied to timber boards located at the support, the stress spread throughout the other folds of the CSP. This stress distribution leads to a substantial increase in the overall load resistance of the bridge deck. The maximum load resistance when the load is applied to timber boards is approximately 60 kN. In Figure 5.12,
Figure 5.9. Stress distribution when loaded on CSP without timber boards

Figure 5.10. Stress distribution when loaded on CSP with timber boards

Figure 5.11. Stress distribution when loaded on timber boards
5.4 Simplified Method of Estimating Resistance

5.4.1 Stress estimation

In Figure 5.13, where a central load of 80 kN is applied to the bridge deck with 45 mm thickness timber boards and 1.5 mm thickness CSP, it can be observed that the load primarily affects several corrugated folds, leading to concentrated stress in those areas. If the bridge deck is considered as a simply supported beam with the same cross-section properties as the affected folds, the maximum bending moment in midspan can be calculated from the formula:

\[ M_p = \frac{PL}{4} \]  \hspace{1cm} (5.1)

where:
- P - External concentrated load, which is set to 40 kN
- L - Span length of bridge deck

In the real case of bridge deck, assume the maximum stress does not exceed the strength of steel \( f_y \), which means the CSP does not yield. A fictitious elastic section modulus \( W_{fict} \) is set to calculate the maximum bending moment:

\[ \frac{M_p}{W_{fict}} = \sigma_p \]  \hspace{1cm} (5.2)

From equation 5.1 and 5.2:

\[ W_{fict} = \frac{M_p}{\sigma_p} = \frac{PL}{4\sigma_p} \]  \hspace{1cm} (5.3)

where:
- \( \sigma_p \) - internal stress of the CSP subjected by concentrated load
- \( W_{fict} \) - fictitious elastic section modulus

The schematic diagram of the cross-section is shown in Figure 5.14. When the fictitious section modulus is derived, assume that \( n \) corrugated folds are objected by the concentrated load:

\[ n = \frac{W_{fict}}{l_{eff} \cdot b} \cdot z_{edge, max} = \frac{PL \cdot z_{edge, max}}{4\sigma_p l_{eff} b} \]  \hspace{1cm} (5.4)

\( z_{edge, max} \) – maximum distance from the neutral axis to the outer edge of the cross-section
$I_{eff}$ - effective moment of inertia, which can be checked in products sheet from the manufacturer company, and the unit of $I_{eff}$ is mm4/mm obtained from Table 2.2 in Chapter 2, so it needs to be multiplied by width of corrugated folds to get the total moment of inertia in calculation $b$ - width of one corrugated fold, which is 427 mm obtained from Figure 5.1.

Figure 5.13. Stress distribution loaded by 80kN

Figure 5.14. Elastic moment resistance of cross-section of the CSP

From Figure 5.14 it can be seen that the value of $z_{edge,max}$ must be either equal to or greater than half of the height of the CSP. Assuming that $z_{edge,max}$ is equal to half of the height, can indeed lead to larger calculated stress $\sigma_p$ from equation 5.4 when the other parameters remain the same, which tends to provide a more conservative and safer estimation in the design process. Set:

$$z_{edge,max} = \frac{h}{2}$$  \hspace{1cm} (5.5)

where:

- $h$ - height of the CSP, which can be used as 203 mm obtained from the cross-section of TP200

Then the coefficient $k$ of the equivalent stress by $n$ folds can be calculated and if $k = 1$, that means the stress from estimation calculation is equal to that from simulation. The formula of $k$ is derived:

$$k = \frac{\sigma_{FEM}}{\sigma_p} = \frac{8\sigma_{FEM}I_{eff}bn}{PLh}$$  \hspace{1cm} (5.6)

where:

- $\sigma_{FEM}$ - internal stress of the CSP from simulation results
According to the simulation results of stress at the center of the bridge deck, the stress is shown as Table 5.1. Using these stress values, the calculation of the values of k can be performed from equation 5.6, resulting in a diagram shown as Figure 5.15. The diagram illustrates the relationship between the values of k and the number of folds used to estimate the actual bending moment in the CSP. According to this figure, Table 5.2 can be derived when k is set to 1. This table allows engineers to determine the number of folds that can be considered in estimating the actual bending moment within the CSP. Then it will be easier to have a preliminary comparison to the design resistance of bending moment obtained from product information sheets from the manufacturer.

Table 5.1. Actual stress calculated from ABAQUS

<table>
<thead>
<tr>
<th>Thickness of timber boards (mm)</th>
<th>Stress at the center of the CSP (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>336.5</td>
</tr>
<tr>
<td>40</td>
<td>241.6</td>
</tr>
<tr>
<td>60</td>
<td>186.2</td>
</tr>
<tr>
<td>80</td>
<td>136.2</td>
</tr>
<tr>
<td>90</td>
<td>116.8</td>
</tr>
</tbody>
</table>

Figure 5.15. k – thickness of timber boards diagram according to bending moments

Table 5.2. The values of n when k=1

<table>
<thead>
<tr>
<th>k = 1</th>
<th>Thickness of timber boards (mm)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
<td>6</td>
</tr>
</tbody>
</table>
5.4.2 Deflection estimation

It is similar to estimate the maximum deflection by this simplified method. The maximum deflection of a simply supported beam can be calculated from:

$$\delta_p = \frac{PL^3}{48EI_{eff}bn}$$  \hspace{1cm} (5.7)

where:

- $E$ - modulus of elasticity
- $\delta_p$ - maximum deflection of the simply supported beam
- $I_{eff}$ - effective moment of inertia, which can be checked in products sheet from the manufacturer company, and the unit of $I_{eff}$ is mm$^4$/mm obtained from Table 2.2 in Chapter 2, so it needs to be multiplied by width of corrugated folds to get the total moment of inertia in calculation
- $b$ - width of one corrugated fold, which is 427 mm obtained from Figure 5.1.
- $n$ - the number of corrugated folds which are assumed to be subjected by the concentrated load

The coefficient of the equivalent maximum deflection by $n$ folds can be calculated from:

$$k = \frac{\delta_{FEM}}{\delta_p}$$  \hspace{1cm} (5.8)

where:

- $\delta_{FEM}$ - maximum deflection obtained from simulation results

From equation 5.7 and 5.8, $k$ can be calculated from:

$$k = \frac{48\delta_{FEM}EI_{eff}bn}{PL^3}$$  \hspace{1cm} (5.9)

The actual maximum deflection is shown in Table 5.3. Therefore, the values of $k$ can be calculated, shown as Figure 5.16 and Table 5.4 is obtained when $k=1$. From Table 5.4 it can be seen that in design process, the same values of $n$ can be used to estimate the bending moment and maximum deflection of the bridge deck.

Table 5.3. Actual max. deflection calculated from ABAQUS

<table>
<thead>
<tr>
<th>Thickness of timber boards (mm)</th>
<th>Maximum deflection at the center of the CSP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20.88</td>
</tr>
<tr>
<td>40</td>
<td>15.55</td>
</tr>
<tr>
<td>60</td>
<td>11.51</td>
</tr>
<tr>
<td>80</td>
<td>8.6</td>
</tr>
<tr>
<td>90</td>
<td>7.31</td>
</tr>
</tbody>
</table>
5.5 Serviceability Limit State of designed bridge deck

The SLS analysis of the timber-CSP bridge deck is conducted utilizing the designed dimensions of bridge deck, the 1.5 mm designed thickness of the CSP and 45 mm designed thickness of timber boards which is mentioned in Chapter 5.1.

5.5.1 Load Combinations

For the purposes of this master’s thesis, only the following loads are considered:

- Crowd load: \( q_c = 5kN/m^2 \)
- Self-weight: \( q_{self} = 0.211 + 420 \times 9.8 \times 0.001 \times 0.045 = 0.396 kN/m^2 \)

Designed uniformed load:

\[
q_{Ed} = 1.35 \times q_{self} + 1.5 \times q_c = 8.03 kN/m^2
\]

5.5.2 Results

The deflection of bridge deck under designed uniformed load is shown in Figure 5.17. According Eurocode 5 EN 1995-2, limiting values for deflections for plates are shown in Table 5.5.
Table 5.5. Requirements for deflections in Eurocode 5

<table>
<thead>
<tr>
<th>Action</th>
<th>Range of limiting values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic traffic load</td>
<td>L/400 to L/500</td>
</tr>
<tr>
<td>Pedestrian load and low traffic load</td>
<td>L/200 to L/400</td>
</tr>
</tbody>
</table>

The maximum deflection can be checked from the figure:

\[ u_{\text{max}} = 9.206 \text{ mm} < \frac{L}{200} = \frac{400}{200} = 20 \text{ mm} \]

Therefore, the maximum deflection meets the requirements.

The stress distribution is shown in Figure 5.14 and the maximum stress is 198.2 MPa. Assume the value of \( z_{\text{edge, max}} \) is \( h/2 \), which is smaller than the real value. The maximum moment \( M_{Ed} \) can be calculated from the equation 5.2:

\[ M_{Ed} = \frac{\delta_{FEM} \cdot I_{eff}}{z_{\text{edge, max}}} = \frac{S \cdot I_{eff}}{h/2} = 27.47 \text{ kNm/m} \]

where:

\( \delta_{FEM} \) - maximum deflection obtained from simulation results
The bending moment can be compared to designed value obtained in product information sheets from ArcelorMittal Construction:

\[ M_d = 45.94 \text{ kNm/m} \]

\[ M_{Ed} < M_d \]

Therefore, the designed bridge deck in this thesis meets all the requirements.
This thesis investigated the structural behavior and performance of the designed timber-CSP hybrid bridge deck. Through laboratory tests and finite element simulations, the study involves various aspects such as load resistance, deflection, stress distribution and the effect of various parameters. The results of laboratory tests demonstrated that the timber-CSP hybrid bridge decks offer promising potential as an alternative to conventional bridges. The inclusion of timber boards significantly increases the load-bearing capacity and stiffness of the bridge deck. The different boundary conditions of the edges screwed to supports has no evident influence on the performance of bridge deck.

The simulations closely match the laboratory test results, validating the accuracy and reliability of the FE models. Parametric studies of ULS analysis show the changing curves of different thickness of timber boards and corrugated steel plates, demonstrate their significant impact on the load resistance and structural performance of bridge deck. The maximum deflection and bending moment in SLS analysis meet the requirement from Eurocode and the manufacturer.

Additionally, the investigation of the stress distribution and deflections provides a simplified method for engineers to estimate actual bending moments and maximum deflection during the preliminary calculation in design process, determining the number of folds to consider. As for the designed bridge deck with 1.5 mm thickness of the CSP and 45 mm thickness of timber boards, 3 folds can be used to be considered as a simply supported beam to do the preliminary calculation of bending moments and deflections.

When creating a FE model using various software, it is crucial to prioritize the validation of the model’s feasibility and reliability. Therefore, laboratory tests should not be overlooked during research on the structural behavior, particularly when considering timber as a material that is hard to predict based on the design properties due to its imperfections and other factors. Consequently, laboratory experiments serve as an essential cornerstone in timber structure research. By comparing the results obtained from laboratory tests with the predictions of the FE model, researchers can assess the accuracy and dependability of the model in observing the real-world behavior of timber structures. Moreover, laboratory experiments enable the study of failure modes that cannot be fully captured from theoretical models. Through the combination of experimental testing and numerical analysis, a more comprehensive and reliable understanding of the structural behavior of timber systems can be achieved.
7 RECOMMENDATIONS AND FUTURE WORK

- Further development of the real bridge deck modelling as well as the laboratory tests of full dimensions of bridge deck
- Connections between timber boards and corrugated steel plate analysis.
- Further studies on the vibration resistance, durability, and sustainability of the hybrid bridge deck.
- Failure mode prediction of the hybrid bridge deck and possible remedies
- Validation of the simplified method on different types of CSPs and different classes of timber.
- Some new designing configurations such as double CSP that significantly increases the stiffness of the bridge deck.


