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AUTHOR(S) Sissel Sandaker	SUPERVISOR(S) Aase Reyes Katalin Vertes

IN COLLABORATION WITH	CONTACT PERSON
Light Structures AS	Geir Sagvolden

SUMMARY / SYNOPSIS

The Digital Twin concept has a lot of potential to offer the construction industry, however there is still need for a research effort to ensure implementation is done in a satisfactory way. Many disciplines need to contribute in this research to ensure that all stakeholder needs are considered and met. This thesis focuses on researching how the concept can contribute to the structural aspect, and specifically by supporting structural health monitoring of ageing bridges. The thesis has two parts: First a literature study of the promising concept. The second part is a case study concerning a concrete box girder bridge located in the west coast of Norway. The bridge is 3D scanned, modelled and analysed as the first step of creating a digital twin.

KEYWORDS
Digital Twin
Structural health monitoring
Bridge

Project assignment Spring 2022

Sissel Sandaker

Assessment of Digital Twin as a tool in Structural Health Monitoring of ageing bridges

The idea of the use of digital twin in structural engineering and the construction sector has been increasingly popular. In other sectors they have come much further in the development of digital twins. However, some work has been done in structural engineering, e.g., in the monitoring of bridges. How can the construction industry learn from other sectors when it comes to developing digital twins for structures? This topic will be studied further in the present project.

The project can consist of some (not all) of the following activities:

1. Theory and literature study about digital twins.
2. State-of-the-art on digital twins within structural engineering
3. Case study of existing bridge with sensors
    a. Evaluation of existing sensor data
    b. Modeling of the load bearing structure in ABAQUS
    c. BIM modeling of the bridge

The candidate can focus the work on specific parts of the assignment, or assess other aspects in consultation with the supervisors.

The form of the report will be as a scientific research report where emphasis is placed on a clear and well-arranged presentation.

Supervisors: Aase Reyes & Katalin Vertes, Oslo Metropolitan University
Dr Geir Sagvolden, Light Structures AS

The report is due at the Department of Civil Engineering and Energy Technology at May 25 2021.

OsloMet, January 5 2022

Aase Reyes, Katalin Vertes & Geir Sagvolden
Supervisors

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Sissel Sandaker

Abstract

The need to travel from one place to another is a fundamental pillar of our society. Since the beginning of time, humans have altered their surroundings to get from A to B in a more efficient way. Often, this pursuit of accessibility would involve the great challenge of building a bridge. Even today this is seen as a challenging task, due to factors such as ever-increasing traffic loads, lack of resources and climate change. The latter is also an important reason for the need to maintain existing bridges instead of demolishing them, which would cause large CO_2 emissions.

Recently a new concept has grown in popularity within the construction industry; Digital Twin, which offers a new level of control over our assets. The Digital Twin concept offers the possibility of updating the digital model by IoT technology as well as simulation of what-if-scenarios. For a bridge, the positive outcomes of having a digital twin can be increased safety, decrease in maintenance cost and extended service life.

Osstrupen Bridge, a prestressed box Girder Bridge that has been strengthened by an internal tubular arch due to an excessive sag is studied in the context of the Digital Twin concept. The mounted support system within the bridges cavity is equipped with sensors. By utilizing these sensors, a step in the direction of a digital twin for the structure can be made.

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List of abbreviations

BIM – Building Information Modelling

AI – Artificial Intelligence

IoT – Internet of Things

SHM – Structural Health Monitoring

FBG – Fiber Bragg Grating

PLM – Product Lifecycle Management

FEM – Finite Element Modelling

FEA – Finite Element Analysis (sometimes also noted as FE Analysis)

NPRA – The Norwegian Public Roads Administration

CAD – Computer Aided Design

UAV – Unmanned Aerial Vehicle

WSN – Wireless Sensor Network

SD – Standard Deviation

Chapter 1 Introduction

The need to travel from one place to another is a fundamental pillar of our society. Since the beginning of time, humans have altered their surroundings to get from A to B in a more efficient way. Often, this pursuit of accessibility would involve the great challenge of building a bridge. Even today this is seen as a challenging task, due to factors such as ever-increasing traffic loads, lack of resources and climate change. The latter is also an important reason for the need to maintain existing bridges instead of demolishing them, which would cause large CO_2 emissions.

The public may perceive these important structures as passive and inanimate objects, but they do in fact experience motion, injuries, corrosion, and they deteriorate with age. Unfortunately, with these, often enormous structures, the devil is in the detail. Imperfections that can be hard to observe, even with a skilled eye, can prove to be of catastrophic importance.

Recently a new concept has grown in popularity within the construction industry; Digital Twin, which offers a new level of control over our assets. Today, the industry is deploying Building Information Modelling technology (BIM), in many projects. BIM offers a lot of control over the design phase and allows for better management of materials. However, the Digital Twin concept offers the possibility of updating the digital model by IoT technology as well as simulation of what-if-scenarios. For a bridge, the positive outcomes of having a digital twin can be increased safety, decrease in maintenance cost and extended service life, which is a huge benefit regarding CO_2 emissions.

1.1 Motivation

The average age of bridges in Norway is 46 years, 21% of our 17.367 bridges are built before 1960 [1]. Thus, a large number of our bridges are collectively approaching their defined end of service life. (For more data on bridges in Norway see Appendix A) To avoid enormous CO_2 emissions due to demolition and rebuilding these vital assets, an increased effort should be made to evaluate the possibility to extend their service life. However, to extend a bridges' service life without compromising safety, requires thorough assessment of the condition of the bridge. Today assessments of bridges in Norway, consists mainly of scheduled visual inspections. Non-destructive testing can be initiated based on the findings of the visual inspection [2]. However, this methodology can have limitations. A new field of research that has shown inspiring results in other industries is now being applied to projects within the construction industry to try to meet these shortcomings, and that is the Digital Twin concept.

Based on the success stories from Digital Twin concepts in other industries, it can be assumed that this technology has a promising prospect towards the construction industry. This potential could be extending service life of some bridges, the safety level could be increased, as incidents or critical damages to the bridge could be detected in “real-time” in contrast to being detected in a scheduled visual examination. In addition to this there is also a great research value that can be found in utilizing digital twin, as they have the possibility to give a better overview of the complex system that a bridge is. It can educate us on how the bridge reacts to many different scenarios with more factors taken into the equation, like its up-to-date conditions and damage history. A digital twin can be a tool to help make decisions based on more and better data than what is the case today.

In the construction industry creating digital twins for aging bridges are high yield projects, they are complex systems with often complex degradation and damage scenarios, and the consequences for missing damage detection can be catastrophic. It can easily be assumed that there can be huge savings with creating a digital twin for an existing bridge that is approaching end of service life, not only economical but also environmental.

This thesis aspires to be a part of this move towards virtualizing structures by utilizing the concept of Digital Twin.

1.2 Problem statement

The Digital Twin concept has a lot of potential to offer the construction industry, however there is still need for a research effort to ensure implementation is done in a satisfactory way. Many disciplines need to contribute in this research to ensure that all stakeholder needs are considered and met. This thesis focuses on researching how the concept can contribute to the structural aspect, and specifically by supporting structural health monitoring of ageing bridges. Some of the questions sought to be answered are the following: What are the possibilities and challenges in our pursuit to enabling the concept? What value can the concept vitalize? And what can we learn from other industries that have come further in utilizing the concept with great outcomes?

The governing questions driving the case study is: Can a digital model for the bridge in question be established by utilizing the sensors that are monitoring the support structure? What assessments needs to be considered when initiating a digital twin for the bridge?

1.4 Scope and Limitations

The objective of this thesis is to look at the possibility of using the Digital Twin concept as a tool to support structural health monitoring. Researchers have said since the 90's that we need to measure the real performance of the bridge rather than just rely on qualitative visual inspection results which are highly variable and subjective [3].

The outcome of this thesis is not a functional digital twin of the bridge in question. The thesis is aiming to be a first step in the process of creating one. Creating a digital twin of a structure like a bridge is a complex task that requires collaboration between many disciplines. The first part of this thesis seeks to highlight the background, the possibilities and the limitations, the available tools, and the ongoing research of the concept. In the second part of the thesis the concept is being evaluated towards a physical structure where sensors already are mounted. The outcome goal here is to create an updated digital model of the structure in question, highlight the available possibilities and challenges regarding creating a digital twin of the asset with the already mounted sensors.

When a digital twin project is initiated, the very first step must be to make a clear definition of what objective and outcome the digital twin is to provide. What value can the digital twin bring to the asset? What is to be measured, where should it be measured and how often, etc.? In the case study of this thesis the situation is reversed. The structure already has sensors installed. The main objective of the added sensors was initially to carefully monitor the jacking process. However, evaluating this "backwards" scenario could be relevant as some bridges already have sensors mounted for structural health monitoring purposes, and creating a digital twin from scratch might not always be the case. So, the questions that then arises are: Can these sensors contribute to a digital twin system for the bridge without too much intervention, what information could it provide and is it worth the effort?

Many simplifications to the digital model of the bridge (the concrete parts) were made, as a detailed model of the bridge is not a part of the scope. The abutments on each side of the bridge have not been taken into consideration in the model. Also, the tendons anchoring the cantilever arms to the mountain has not been considered in this thesis.

There were sensors added to both frames and arches on the support structure. The original sensor configuration on the frames did not give the desired results in terms of inference of the lifting forces transferred from the arches to the bridge. New sensors, installed in another set of locations at a later stage, gave excellent results. The sensors mounted on the arches were stable and they provided consistent data. Therefore, the sensor data from the frames will not be evaluated further in this report.

1.5 Methodology

This thesis consists of two methodologies: a literature study and a case study.

The concept in question is currently undergoing a massive research effort from many industries, so the concept is gaining new definitions, new tools, and new frameworks rapidly. The literature study was carried out to ensure that the author was updated on the latest research. In addition, the literature research was aimed towards the specific objective for the concept, structural health monitoring.

The case study will be carried out by an excursion to the bridge to scan the geometry, the scans will be used for creating a digital model, which will be analysed.

1.6 Thesis Structure

The thesis is divided in two parts, where Part I is a literature review, and Part II is a case study.

In Part I, the first chapter will describe the Digital Twin concept, how it came to life and how it is currently defined. It will also list some cases from other industries that have already implemented the concept and seen real value. The current research within the Digital Twin concepts in construction will also be described. In the following chapter some of the tools needed to enable a digital twin will be described. A vital part of the Digital Twin concept are sensors. The sensor technology used for the case study, fiber optics sensors and in particular the Fiber Bragg sensor, will be described in chapter 4.

In Part II a concrete box girder bridge located in the west coast of Norway is evaluated in the context of the Digital Twin concept. First chapter is background about the bridge in question. Then the bridge was scanned, modelled, and analysed, all of which is described in chapter 6. Chapter 7 contains a comparison of sensor output with regards to weather statistics. Chapter 8 contains the concluding remarks.

PART I

Digital Twin

Chapter 2

Concept

20 years ago, Michael Grieves held a presentation regarding Product Lifecycle Management (PLM), and this is where his "Conceptual Idea for PLM" was first introduced. This is recognized by many [4-14] as the starting point of the concept now known as Digital Twin. However, it was not Grieves who came up with the term "Digital Twin". After "Conceptual Idea for PLM" he later named the concept "Mirrored Spaces Model" [15] and then "Information Mirroring Model" before his co-author, John Vickers a scientist from NASA used the term "Digital Twin" in an article he and Michael Grieves wrote together [16]. Figure 1 illustrates the development of the term until it eventually seemed to get widely accepted based on the rapid use in research. (Tuegel et al., Knezevic et al., and CIRP Encyclopaedia is mentioned further in chapter 2.1).

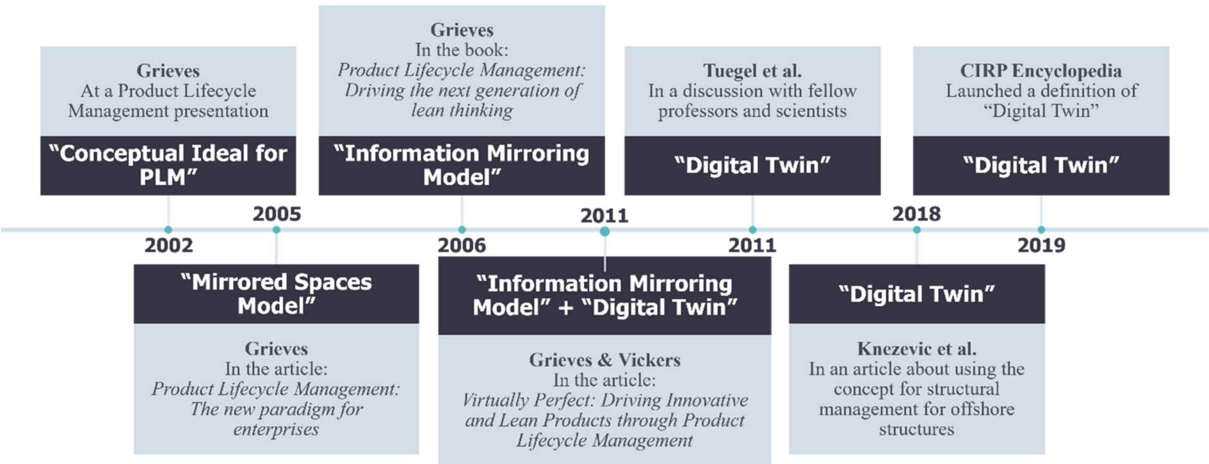

Figure 1: Development of the term Digital Twin

Remarkably, more than 30 years prior to Michael Grieves presentation NASA had a similar concept for their space mission Apollo 13; several simulators that were used to train the astronauts and mission controllers in every aspect of the mission, including multiple failure scenarios. What distinguished these simulators from regular simulator, and the reason for these to be called, by some [8, 11, 17], "The first real digital twins", is that the NASA mission controllers were able to rapidly adapt and modify the simulations based on data from then state-of-the-art telecommunication technology. This made the simulations match the conditions on the real-life crippled spacecraft, so they could research, reject, and perfect the strategies required to bring the three astronauts safely home [17]. This example also demonstrates the potential value of digital twin technology, and that even with the computational power and limited sensor equipment available in 1970 the technology proved to be of vital importance.

Lately the concept has grown exponentially in popularity as one industry after another realise the potential benefit. This has led to many different definitions of the concepts and some of them will be described in the next chapter.

2.1 Definition

The broad spectre of industries orderly realising the potential benefits of the Digital Twin concept, and also the different maturity stages of the industries based on where they are currently at (i.e., research stage, proof of concept stage, deployment stage, utilization stage) generates a large variety of definitions of the concept. In this chapter some of the different definitions that has occurred during the literature search for this study will be listed. Lastly, an evaluation of which of them that covers the concept most in full will be performed.

The aviation and aerospace industry were early to adopt the concept. In 2011 Tuegel et al. [18] describes the concept in great detail while also claiming that in fact they are the ones that came up with the term "Digital Twin" during a discussion between the main author of the article and some of his fellow professors and scientists. Further, the article doesn't state a specific definition, but they do close the article off by stating their vision for the concept: *"The Digital Twin will enable better management of an aircraft throughout its service life. Engineers will have more information about the condition of the aircraft and have it sooner. This will allow better maintenance decisions to be made in a timely manner"*.

In 2012 two researchers from NASA and the U.S. airforce, Glassegen and Stargel [19] constructed a definition as follows: *"an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding twin"*

Several years later, in 2018, the concept was being researched by engineers within the offshore industry. Knezevic et al. [20] wrote an article about using the Digital Twin concept for structural integrity management for offshore structures. They do not provide a definition of the concept in their article. However, this illustrates that the concept now had reached other industry areas.

Digital Twin Consortium, which is an initiative to drive awareness, adoption, interoperability, and development of digital twin technology, released a definition on December 3rd, 2020: *"A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action. Digital twins use real-time and historical data to represent the past and present and simulate predicted futures. Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems."* [21]

In 2020 the AIAA, the world's largest aerospace technical society published a Position Paper on Digital Twin, where they issued the following definition: *"A Digital Twin is defined as a set of virtual information constructs that mimics the structure, context and behaviour of an individual/unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value"* [22]

In 2021 *"A digital representation of an asset or its components for real-time prediction, monitoring, control, and optimization of the asset throughout its life cycle in order to make more informed decision making"* San et al [23]

However, in an article Parker [9] questions the use of "twins" and suggest that "shadow" would be a better fit for when the concept is used for structural health monitoring for bridges. In his paper three models are characterized: digital model, digital shadow and digital twin. Where the digital model has no update feature towards the physical structure, meaning a change in the physical structure will not be reflected in the digital model and vice versa. The digital shadow is a digital representation of an asset that updates with a one-way flow, meaning that a change on the physical structure will be reflected in the digital shadow. Lastly, in the Digital Twin concept the dataflow is both ways, meaning a change in the physical structure will be reflected in the digital twin and vice versa. Parker continues to argue that bridge owners likely do not want a full digital twin as defined here. This would mean that the digital twin changes the physical bridge in automatic real-time modifications. Also, how would these modifications be done? Unlike a process or a machine there is few, if any actuators, or valves on a bridge to adjust.

This just shows that the definition is not yet locked and maybe each industry could benefit from creating their own definition. In fact, buildingSMART Norway, an advocacy group for digitalization of the construction industry, are having a workshop the 15th of June this year where their intent is to come to an agreement on the definition of the Digital Twin concept for the construction industry in Norway [24].

To conclude, the first definitions mentioned above were influenced by their respective industries e.g., the use of the word "vehicle" or "fleet". Later, the definitions moved towards being more inclusive and general. The definition provided by the Digital Twin Consortium is well thought out and seems to apply well to most use cases.

2.2 Tools

Internet of Things

Internet of Things (IoT) is the system of physical objects that are embedded by sensors and software that provides connection and access to information from the physical world to the digital world. Basically, IoT is contributing to bridging the physical-digital divide, which is the very essence of the Digital Twin concept.

Big Data

Volume, velocity and variety makes up the characteristics known as the 3Vs of Big Data. The first V is for volume, and it refers to the significant amount of data produced at a very high speed, thus the second V is for velocity. The third V is for variety as the data is heterogenous with structured, semi-structured or unstructured nature, meaning high variability of data types and formats. A fourth V that could be taken into the characteristics is value, however this requires big data analytics which is a process that analyses the big data and converts it to valuable information. Big Data brought forth a world of new challenges; capturing, storing, sharing, managing, processing, analysing and virtualizing data of high-volume, high-velocity and diverse variety [6].

Reduced Order Modelling

Reduced Basis FEA is a technique for component-based model order reduction, that is used to reduce computational complexity

- The large model is decomposed into components.
- Each component is given parameters that can be modified.
- A reduced order model of each of those components is prepared based on an automated pre-analysis of the individual components and groups of components.
- The component-based models are assembled and solved efficiently due to re-use of the reduced order model data. [25]

Artificial Intelligence and Machine Learning

The concepts of Artificial Intelligence (AI) and Machine Learning (ML) were proposed at the Dartmouth Conference in 1956, aiming at enabling machines to learn rules from historical data and then apply them in the future. In the conference it was proposed that: *"every aspect of learning or any other feature of intelligence can be so precisely described that a machine can be made to simulate it"* [26].

ML can be seen as a subset of the broader category of AI, as AI is defined as the digital replication of three human cognitive skills: learning, reasoning, and self-correction. ML is the scientific study of algorithms and statistical models that help computer systems perform tasks effectively without being explicitly programmed to do so, and instead it relies on learning from historical data converting it to actionable information [6, 13, 25, 26]. These types of algorithms have shown their immense potential for pattern recognition and anomaly detection in multiple areas [27].

Cloud Computing

A digital twin of a large structure with hundreds of sensors generates enormous amount of data, quickly surpassing the ability of any computer to process. Cloud computing meets this challenge and provides cloud-based platforms. These platforms, PaaS (Platform as a Service), allows the user access to a wide range of services with the only requirement for the user is to have an internet connection [27].

2.3 Digital Twin for bridges – ongoing projects

2.3.1 smartBRIDGE Hamburg

Wenner et al. [28] wrote a paper on the pilot project smartBRIDGE Hamburg describing the initiative to create a large-scale demonstrator to implement and experience the concept of the Digital Twin. The bridge Köhlbrandbrücke is one of the most important ones in Hamburg Port and its great size and structure complexity makes it an ideal showcase. A multidisciplinary team consisting of experts within the fields of bridge construction, maintenance and inspection, software architecture, monitoring, data science is working to enable the expected innovation

In the project so far, they have identified six decisive steps to realise a digital twin of an infrastructure asset:

- Structural Health Monitoring (SHM) as a major source of condition monitoring
- The aggregation of the measurement data, the key to generate consumable information
- The fusion of information coming from conventional bridge inspection and from SHM
- The role of Building Information Modelling (BIM) in realising a digital twin
- The data architecture and data management as technical backbone of the digital twin
- The Human Machine Interface: key of the success and acceptance of the digital twin

To read more about the ongoing project see [29]. (Deutsch only)

2.3.2 Mohammed VI Bridge

Sofia et al. [5] describes how they created an updated digital model of the Mohammed VI Bridge in Morocco, the longest cable-stayed bridge in Africa. The study proposes a workflow for structural health monitoring by combining the digital twin, mobile mapping, building information modelling and machine learning. By using an automated mobile mapping system, they captured the real structure by having a Dynamic Lase Scanner mounted on a car and driving over the bridge. The generated output of this fieldwork was one combined georeferenced point cloud of the bridge. They then used the point cloud to create a digital replica in a CAD application which allowed them to study future performance of the bridge under different environmental conditions.

They aim to create a digital twin for the bridge, and in their paper, they further suggest a sensor scheme and a framework for the digital twin.

2.3.3 Railway Bridge in Stafford

The bridge studied in the article by Broo et al. [7], is a railway bridge that is part of the Stafford Area Improvements Programme. The digital twin project for the bridge has an interdisciplinary approach with structural engineers, software developers, data scientists, computer vision researchers, academic leads, and asset managers all participating the frequent project meetings. The sensing system installed on the bridge was installed during construction and was designed to monitor both the construction phase as well as the operation phase. Such an early adoption of sensing system allows the digital twin to create an invaluable baseline from the undamaged structure that can be used for future comparison. The article describes the digital twin implementation in detail from both physical and cyber perspectives. In the conclusion of the article, they put emphasis on the fact that digital twins help close the knowledge gap between different stakeholders from different technical backgrounds, which makes collaboration less challenging.

2.3.4 The bridge over the Bjørnarfjord – Ferryfree E39

In the ambitious project that Ferryfree E39 is, the biggest challenge is to cross the Bjørnarfjord. The fjord is 5 kilometres wide and has depth of up to 600 meters, and a bridge here will reduce the time it takes to get from Stord to Os from 90 minutes to 30 minutes. The current concept is a pontoon bridge, also called a floating bridge. In this project they look at using digital twin technology to contribute to maintenance. The project is planned to start in 2024/2025 under the condition of sufficient political attention and funding [30, 31].

2.3.5 Discussion

Based upon the projects mentioned above it can be concluded that the Digital Twin concept has found its way to bridge engineering. However, the projects are mainly in the start-up phase with still a way to go before actual gain is achieved.

2.4 Current use in other industries

The development of the Digital Twin concept has come much further in some industries, and thereby several different methodologies and state-of-the-art has been established. The construction industry could benefit from learning from these use cases. In this chapter some projects will be described briefly. The following projects have also been described in the literature study done by the author for the course *MABY5010 Structural Engineering Specialisation* at OsloMet [32].

2.4.1 Offshore and Marine Industry

In 2018 Knezevic et al. [20] presented a method that enables high-detailed condition-based analysis of floating structures like the semi-submersible seen in Figure 2. These are large and very complex structures subjected to harsh environment. In addition, these structures are often operated beyond the original design life and inspection and maintenance are often based on ad-hoc rules with significant uncertainties. Consequently, these structures subject a large risk to the safety of the crew and the environment.

Figure 2: Semi-submersible floating drilling rig[1]

Performing a conventional detailed FEA on these structures with millions of degrees of freedoms, is not achievable due to lack of computational power. However, with the Reduced Basis FEA method, suggested by Knezevic et al., the computational cost is sufficiently reduced. The method is a structural simulation framework based on component-based model order reduction.

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[1] https://www.aoosk.ru/en/products/semi-submersible-drilling-rig-moss-cs-50-mk-ii-severnoye-siyanie/

2.4.2 Space and Air force Industry

In the research article by Tuegel et al. [18] from 2011, they are looking at reengineering the structural life prediction process by fully exploiting digital twin technology. The process they propose utilizes the digital twin to integrate computation of the structural deflections and temperatures in response to flight conditions, with resulting local damage and material state evolution. They also present a concept model of how the digital twin can help assure structural integrity.

2.4.3 Aerospace Industry

Recent research by Kapteyn et al. [25] created a digital twin for an unmanned aerial vehicle (UAV). To demonstrate their technology, they set up a flight path with obstacles for the UAV to safely navigate through. The UAV can choose between an aggressive flight path or a more conservative one to reach the goal location. The aggressive flight path would mean higher structural loads to the UAV, and the conservative naturally is less damaging but takes longer time. The UAV is set to choose between these paths based on the condition of its aircraft wing. As the wing accumulates damage the UAV might have to switch to the more conservative path in order to complete the flight without structural failure.

Their methodology for creating a data-driven physics-based digital twin is to build it up from component-based reduced-order models. They state that this approach scales efficiently to large and complex systems.

2.4.4 Discussion

The projects mentioned above is a small collection of the variety of use of the concept in just a few other industries. The industries presented are of those that are known for having most experience with the concept so far. However, there is still a huge ongoing research effort even in these industries to fully exploit the potential of the concept.

Chapter 3

Creating a Digital Twin

The first step to take when creating a digital twin for an asset is to make a clear and thorough definition of its objective and intended use. This should be assessed by a multidisciplinary work group to ensure that all stakeholders requirements have been taken into account in the proposed solution. It is also vital to make an evaluation of what value the digital twin is intended to bring. The outcome of these assessments should be a definition of which functional parameters (e.g., displacements, stress, moment forces etc.), environmental data (e.g., temperature, wind speed, moisture, etc.), and historical data (e.g., log files, maintenance records etc.) the digital twin should generate.

Next, is to define how the data will be gathered, stored, rendered, interpreted, and visualised. The data can be gathered both from sensors but also from traditional visual inspections. Generating large amounts of data, or Big Data (see chapter 2.2), is no huge concern due to the rapid development within cloud technology. The data can also be rendered in the cloud with the help of Cloud Computing ensuring the analysis run without complications. Interpretation of the large amount of data can with help of AI and ML detect indications of anomalies and damages. Basically, all the digital solutions enabling a digital twin system should be set up and organised to best support efficient data handling. In these early steps it is also vital to think about cyber security. This vital subject is known to often not be fully considered early on, resulting in a costly ad-on security layer to be developed afterwards. Alshammari et al. provides an overview over the latest academic research within this field in their paper [33].

A vital aspect of a successful digital twin is a well targeted sensor layout. The sensor type needs to be chosen by a thorough assessment, to assure it can serve its intended purpose. Each type of sensor has its own advantages and drawbacks, which must be considered with care. The sensors also need to be positioned accordingly on the structure to capture the intended data adequately [27].

If the asset in question has a BIM model, the digital model for the digital twin could efficiently be utilized. In a digital twin scenario, the BIM can provide the basis for visualisation, and provide the ability to put the generated information into a spatial-temporal context [29]. However, the digital model based on a BIM model needs to be extended geometrically and semantically in order to function to the full potential with a digital twin system. However, often there is no BIM model of the structure in question. A possible solution then is to generate the digital model by 3D scanning the structure, and the generated point-cloud can be used as a guide to accurately model the structure in CAD software.

It is important to recognize that digital twin is just a tool, it cannot replace the important work of structural health monitoring carried out by skilled personnel. Digital twin is meant to be used as a tool to help make the maintenance more proactive and less reactive, as damages or potential damage-areas can be identified earlier. The digital model could be used for analysing for what-if-scenarios and it could be used to "look into the future"; it could contribute to finding an answer to questions like "Could this detected defect affect the structure in 5, 10 or 20 years if it is not fixed?" or "What is the criticality of the detected defect?".

When creating a digital twin for a new bridge, the analysis model has a healthy state to use for comparison. However, a bridge is designed for 100 years' service life. Sensors have a service life of 20 years typically, and the electronics have a slightly shorter lifespan. This requires the sensor concept for the bridge to be exchanged/upgraded. The data should be independent on the sensors used. However, it requires a recalibration of the new sensors to "connect" to the time series from the old sensors.

3.1 Building Information Modelling

Building Information Modelling (BIM) has already been implemented to many constructions in Norway. A growing number of companies have it as a default requirement with new projects. Some look at the Digital Twin concept as a natural next step after BIM. A question that often arises is "What is the difference between BIM and Digital Twin?" Figure 3 illustrates an answer to this question. BIM is a system that provides a platform for collaboration between the different disciplines contributing to the different phases of a structures life cycle. In regards of the static information and visualisation, all updates to BIM needs to be done manually. Whereas a digital twin is dynamically linked to the real world by IoT and WSN and can provide up-to-date condition data.

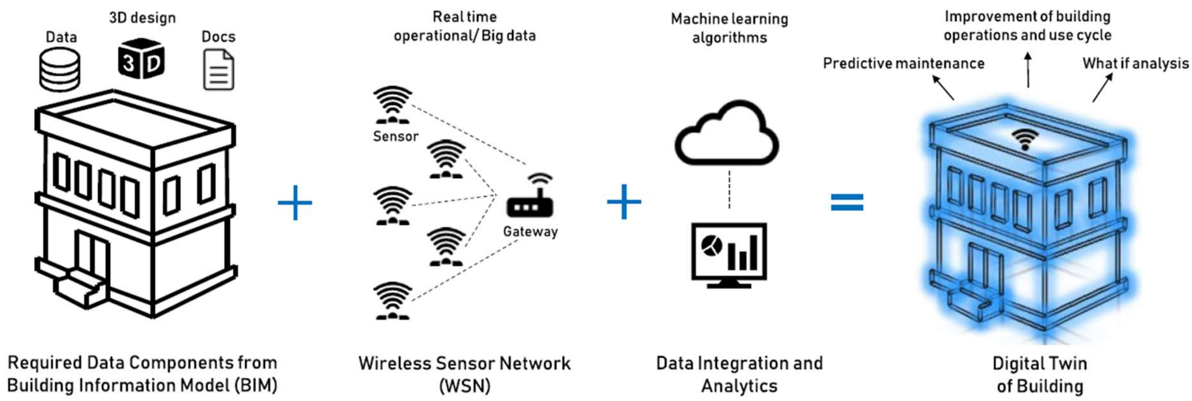


Figure 3: Essential component to create a digital twin of a building and difference with BIM [34]

3.3 Possibilities and Ongoing research

Utilizing the Digital Twin concept for infrastructure would ideally allow for doing maintenance that is more predictive than reactive. Repairing damages after they occur and, more importantly, only after they have been detected by visual inspection, would be considered as reactive maintenance. Often the damage has progressed to a severe character by the point of discovery. Predictive maintenance brings several potential benefits like predictability, controllability, coordination of maintenance that includes prescriptive measures to be taken to avoid the damage to reach a severe grade. Essentially, predictive maintenance is using a digital twin to simulate and anticipate possible future defects and correct the underlying vulnerabilities before the defect occurs [28].

San et al. suggest combining physics-based and data-driven models in a hybrid analysis modelling approach (HAM) in [23]. The frameworks they outline aims at transforming both physics-based and data-driven methodologies into general, robust and portable computational tools for application across different sectors.

Currently there is a research project called “Digital Twin for Infrastructure using Big Data and Smart Sensor Networks” that is carried out as a collaboration between London Digital Twin Research Centre (Middlesex University London) and University of Transport and Communication (Vietnam). Their objectives for this project is to handle the data collection, deploy machine learning and edge computing, and to develop methodology for prognostic health monitoring [35]. The London Digital Twin Research Centre was founded in March 2020.

The newly started Digital Twin Consortium [21] is a collaborative partnership between industry, academia, and government expertise. Their goal is to drive the awareness, adoption, interoperability, and development of digital twin technology. They intend to meet this goal by identifying and filling gaps in the technology development, drive interoperability through frameworks and open-source code, work to influence policy and standards requirements amongst other initiatives.

A benefit that is often overlooked concerning the Digital Twin concept, is the ability to store historical data of the asset. Damage history, repair history, environmental history, loading history are all essential data for predicting future performance of the asset. In addition, if the structure is demolished, structural parts can be assessed with help of the history data to evaluate the possibility to reuse in other construction projects.

3.2 Challenges

Creating the virtual model for the digital twin is a challenge that is receiving a lot of research effort [36]. In addition, the virtual model needs to be updated throughout the lifecycle of the asset. Obtaining the real condition of the state of the bridge is a complex matter. More research is required within these issues as there is exist no efficient and automated method for this to be solved. As monitoring large structures like bridges in near real-time requires creating an analysis model that are computationally efficient [37]

Lack of standardisation is also a challenge. Currently there is no single standard that focuses on digital twinning [6]. However, there is ongoing efforts underway by the joint advisory group of ISO and IEC, and the Digital Twin Consortium is also looking into this issue [21].

The increasing number of benefits and possibilities the rapid development within digital twins and IoT bring, there also occurs a number of security challenges. This is an under-researched area. The digital twin should be able to secure the identity and protection of their physical twin [33]. Preferably, cyber security is considered from project start-up.

When creating a digital twin for an existing bridge structure it is a challenge that the “healthy” state of the structure is lacking, meaning no healthy reference point. It can only evaluate change with respect to the state that was logged at the start-up of the digital twin.

3.3 Updating the Digital Model

When a construction is in its design phase, the digital design, or CAD model is subjected to analysis to verify the design. This analysis is based on many subjective assumptions and simplifications. When the structure is built, the design model might not represent the physical model in an adequate manner. By model updating, which intends to be a digital twin technology, you integrate your collected measurement data with your digital model. For example you can create an analytical model of the bridge structure [3]

The analysis model needs to be verified after creation to answer the question: "Does the model represent the physical model within a certain accuracy level?" The digital model could be verified by first simulating a load (or several different loading scenarios) being applied to the model, then subjecting the physical model to the same loading scenario(s) and comparing the results, the digital model could be verified if the gap between the results is below a certain accuracy level. If not, investigations to see where the digital model fails to sufficiently replicate the physical model needs to be initiated.

3.4.1 Capture real (as-built) geometry for the Digital Twin

Depending on the objective and desired accuracy of the digital twin it may be required to capture the real geometry of the physical model in question. With regards to structural engineering, it could be assumed that this is more often the case than not, as the geometry is essential in the structural behaviour of the model. In the case of a cantilever bridge, its geometry changes over the years due to creep and shrinkage (degradation). These changes of the structure might affect the structural behaviour of the construction.

In the case study in Part II of this thesis the structure in question is a bridge built in 1976, hence it would be best practice to capture the as-built condition of the structure as the drawings of the bridge most likely does not represent the bridge adequately due to deformations caused by age. If a digital twin were to be created from the drawings entirely it is not likely to represent its physical twin in a desired way.

3.4.2 Laser scanning

A model update solution is to 3D scan the bridge and use the generated point cloud to model the structure. Laser scanners use the time-of-flight from the sensor to the target.

$$d = \frac{t * c}{2}$$

Where d is the distance from the sensor to the surface point, t is the required time it takes for the emitted laser beam to return to the target and c is the speed of light.

There are currently a lot of development within the scanning technology, as with digital twins many industries are also finding use for this technology within their field, making the scanners accessible and affordable.

3.4.3 Model update examples from real projects

In (SOFIA et al) they created a digital twin for the Mohammed VI Bridge in Morocco, the longest cable-stayed bridge in Africa. To capture the geometry, they used a vehicle independent mapping solution that combined LiDAR and high resolution 360° seamless panoramic images. LiDAR is an optical measuring technique that measures the distance to an object by calculating the time difference between the emitted laser signal and the reflected light. With the help of the scanner, they captured the features of the bridge that suffered from major health concerns including local damages such as degradation and corrosion. In that project a digital twin model was seen as a framework to implement new requirements for better bridge maintenance.

Kapteyn et al. [38] uses a library of component-based reduced-order models and interpretable machine learning to estimate which model in the model library that best matches the observed data. This enables data-driven digital twin model adaptation. However, a limitation with this approach is the need to establish the sufficient number of states of all parts of the asset in question to allow for the ability to represent a large number of possible scenarios.

Chapter 4

Structural health monitoring

Structural Health Monitoring (SHM) is a concept that utilizes sensors on the structures that can be used to help understand the behaviour of the respective system and its response to the environmental loads, and optimally it can be used to diagnose their current state, it could give the possibility of prognosing the remaining service life [37]. By equipping the structure with well selected sensors, that are strategically placed, the current condition can be evaluated. This requires that the sensors are connected to IoT-systems and that the data they produce are rendered in an interpretable way. When this data is combined with the data from the classical inspections it should provide the decision-makers a solid platform to base their conclusions upon.

4.1 Sensor Technology

The development within sensor-technology has accelerated and made the products accessible and inexpensive. Most sensors used for SHM measures strain, and this technology is well established. In the construction industry context we are dealing with large structures, so it is preferred to use low-cost technologies that are mature enough to provide information at the level of precision that is required for understanding the performance of these systems [37] However, the advancement in technology has brought forward different systems of sensors; fiber optics, micro-electro-mechanical systems (MEMS) and piezoelectrical. These new technologies have improved quality and digital possibilities [39].

Fiber optics sensors

Sensors based on fiber optics have many advantages, they are lightweight, corrosion resistant and durable amongst other benefits [39, 40]. One of the benefits that are important is that they allow for the ability to monitor more than one damage parameter thus lowering the number of sensors needed.

For more information about sensors applicable for digital twin systems it is referred to the authors literature review [41] which was written for the course *MAEN5300 Research Methods and Ethics* at OsloMet.

4.2 Fiber Bragg Grating Sensors

Within fiber optics sensors the ones based on Fiber Bragg Grating (FBG) are most used [40, 42]. Specific wavelengths are reflected by the FBG, and when the optical fiber is deformed the dimensions of FBG are changed and this consequently alters the wavelength on the reflected waves [40]. These sensors are mainly used for measuring strain or temperature, however by applying transducers they can measure parameters like humidity, pressure, displacement, acceleration, magnetic flux, pH value.

The optical sensor consists of a core, a thin glass fiber, cladding that confines the propagation of light within the fiber core and these layers have a protecting cover that provide mechanical strength in addition protection against moisture [39]. Some other important advantages in addition to the ones already mentioned are that they are immune to electromagnetic interference, and they have a high sensitivity [39, 40, 42] Disadvantages with these sensors are that they are very fragile, and this makes them difficult to install [39]. In addition, they are expensive to build and maintain [40].

The wavelength of a Fiber Bragg Grating Sensor changes with strain and temperature according to [43]

$$\frac{\Delta\lambda}{\lambda_0} = k * \varepsilon + \alpha_\delta * \Delta T$$

$$k = 1 - p$$

$$\alpha_\delta = \frac{\delta n/n}{\delta T}$$

$\Delta\lambda$ = wavelength shift

λ_0 = base wavelength at test start

p = photo-elastic coefficient, p=0.22

k = gage factor, k=0.78

ε = strain

ΔT = temperature change in K

α_δ = change of the refraction index, α_δ =5….8*10^{-6}/K

Explanation of the equations

(k*ε) describes the strain impact caused by force (ε_m (mechanical strain)) and temperature (ε_T)

(α_δ*ΔT) describes the change of the glass refraction index n caused only by temperature

$\Delta\lambda$, the Bragg wavelength shift is given as follows [44]:

$$\Delta\lambda = \frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

Were

p_e = strain optic coefficient (relationship between the applied stress and induced birefringence)

α_Λ = thermal expansion coefficient of the optical fiber

α_n = thermo-optic coefficient

ε = applied strain

ΔT = change in temperature

The refractive index, n, is defined as the ratio of the velocity of the electromagnetic wave in vacuum to the phase velocity of the same wave in the material.

$$n = \frac{c}{v}$$

Where c is the speed of light in vacuum, and v is the speed of light in the material. The variation of the refractive index with the temperature at a constant pressure is called the thermo-optic coefficient, α_n [45].

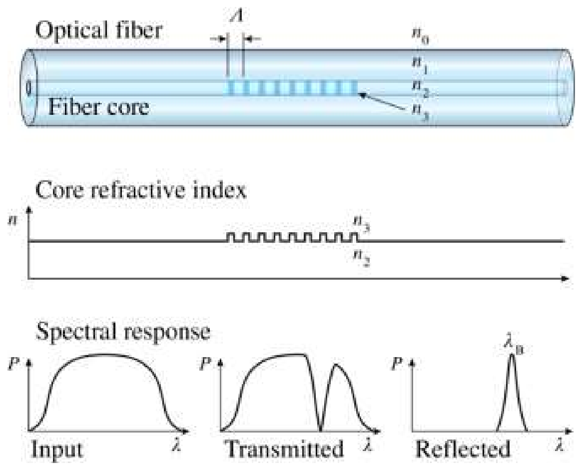


Figure 4: Fiber Bragg Grating Structure, with Refractive Index Profile and Spectral Response [44]

PART II

Case Study: Osstrupen Bridge

Chapter 5

Introduction

Figure 5: Osstrupen Bridge

Osstrupen bridge, seen in Figure 5, was built in 1976, in a rural area on the west coast of Norway. It connects Høydal and Lending over the Høydalsfjord. It is a part of the Stavang-Lending initiative that was agreed upon, in accordance with the road managers recommendation, by the county committee in 1968. This road gave access to many communities along the south side of the Høydalsfjord and provided the residents in Stavang road-access to the municipal centre Florø. The bridge was finished on the 15th of February 1976, and the total cost of came to 7.4 million NOK. At that time the bridge was the longest cantilever bridge in Norway, and the 3rd longest in the world. Interestingly, the remainder of the road project took four more years to complete so the bridge did not open for traffic until 1982. A key factor that influenced the decision of designing the bridge as a cantilever bridge was the low price of steel at the time. Had it been built earlier the bridge most likely would have been designed as a suspension bridge [46].

Today, Osstrupen Bridge is a part of county road 542, a map over the location is seen in Figure 6. The Vestland County Council and the Norwegian Public Roads Administration are responsible for maintaining the bridge.

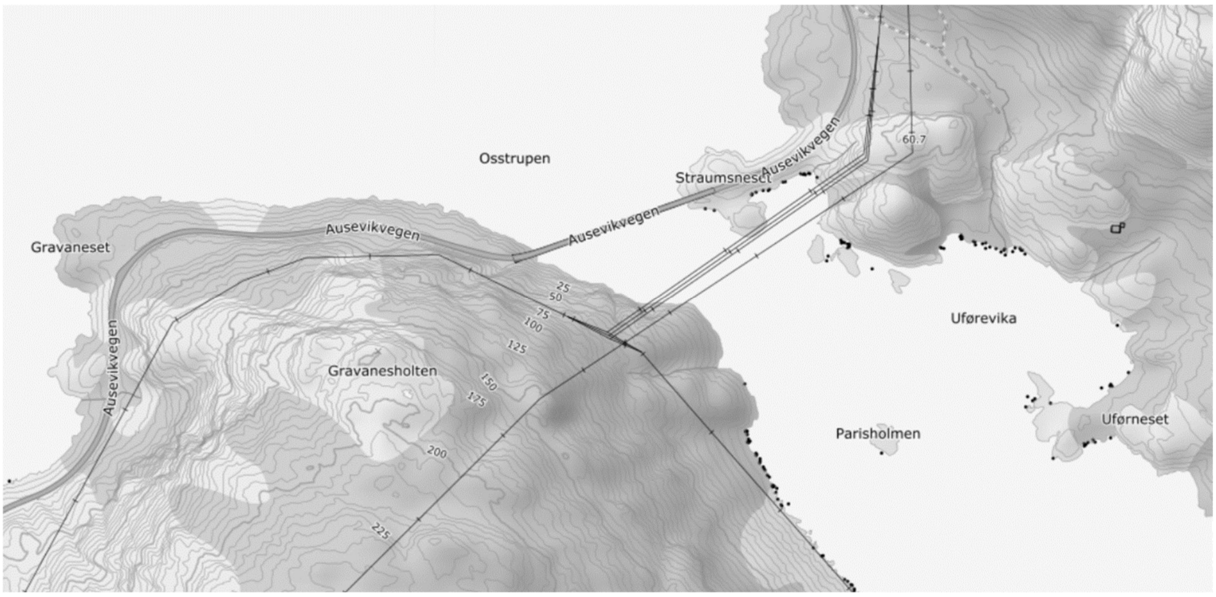


Figure 6: Map over the location of the bridge[2]

[2] Seklima.met.no

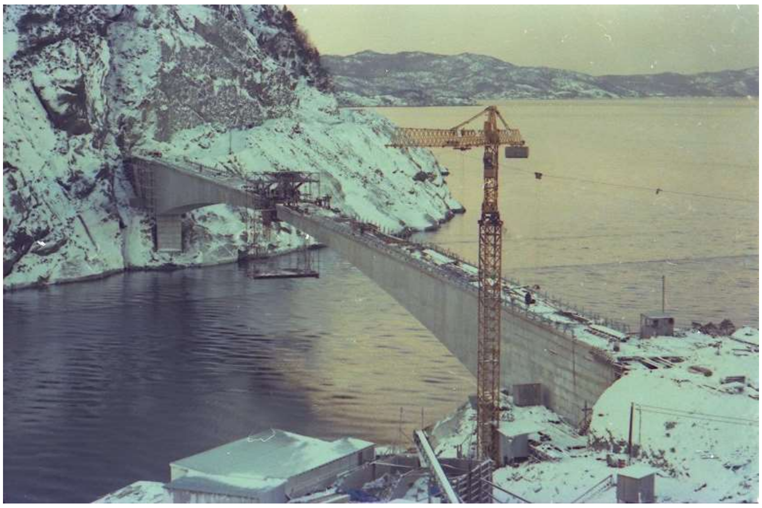


Figure 7: Osstrupen Bridge during construction in 1976[3]

5.1 Bridges in Norway

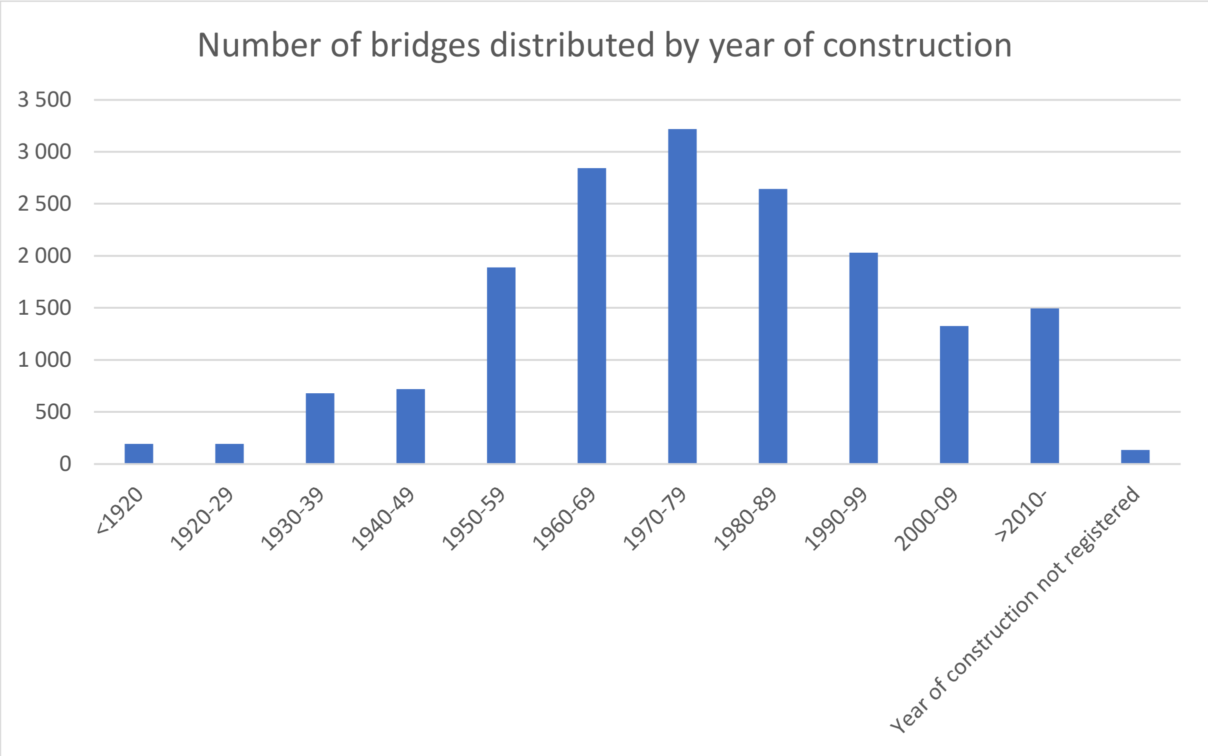
5.1.1 Brief history of roads in Norway

The first vehicle came to Norway in 1896. It was a Benz minibus that had a 4 hp engine and it was put in commercial traffic in Gausdal. The first car was bought in Kristiania in 1899, and the first truck came in 1900. At that time the roads were constructed for horse-carts, so the roads needed many updates, amongst them was that they had to be extended in width to 5-6 meters, and a substantial number of bridges had to be strengthened or re-built. After that, the development of the road network continued steadily, only interrupted by World War II which caused significant damage to the infrastructure. After the war, all efforts were put into repairing the existing roads and it was not until 1950 that they started developing new roads again [47].

[3] Elsa Aarseth, Naustdal Kommune

5.1.2 Norwegian bridge statistics

Table 1: Number of bridges in Norway distributed by year of construction [1]



The situation in Norway regarding bridges is that 3.675 bridges are more than 60 years old, and these bridges make up more than 20% of the total 17.367 bridges in Norway. These bridges include culvert bridges, pedestrian bridges as well as road bridges [1].

5.1.3 Cantilever bridges in Norway

The biggest concrete structures that are created by prestressed beam bridges are called cantilever bridges. The construction method was developed in Germany and was first used in Norway in 1960 when the Tromsø bridge was built. The Stolmasund bridge that was finished in 1998 was once the world's largest bridge of this type with a span of 301 meters [47]. It was surpassed by Shibanpo Yangtze Bridge in Chongqing in China with its 330 meters in 2006. Interestingly, as seen in Table 2, Norway has a total of five instances on the top 10-list over the world's longest prestressed cantilever bridges based on span [48].

Table 2: Top 10 World's Longest Prestressed Concrete Girder Bridges based on span [48]

Rank	***Bridge***	***Span [m]***	***Location***	***Country***	***Year***
1	Shibanpo Yangtze Bridge	330	Chongqing	China	2006

2	Stolmasundet Bridge	301	Årland	Norway	1998
3	Raftsundet Bridge	298	Lofoten	Norway	1998
4	Sundøy Bridge	298	Leirfjord	Norway	2003
5	Beipanjiang Shuipan Bridge	290	Guizhou	China	2013
6	Sandsfjord Bridge	290	Suldal	Norway	2015
7	2nd Humen Bridge	270	Guangdong	China	1997
8	2nd Sutong Bridge	268	Suzhou-Nantong	China	2009
9	Honghe Bridge	265	Yuanjiang	China	2003
10	Gateway Bridge	260	Brisbane	Australia	1986

Cantilever bridges can in theory be built with a span of up to 500 meters, and with the possibility to be built in curves they are the better option for many sites with challenging topology. In addition, since they can be built without high rising towers, they are less jarring to the surrounding landscape [47].

The beams are casted in short sections, often approximately 5 meters, symmetrical over the pillars. Successively each section is added until they meet in the midspan. A formwork trolley carries the sections during construction, and it is moved forward after every section is complete. The work follows a set procedure for every step:

a. tensioning
b. armouring
c. casting
d. hardening
e. tensioning
f. moving the formwork trolley

The sections are supported by continuous tension cables that are anchored in the adjacent span on the opposite side of the pilar [47].

5.2 Design of Osstrupen Bridge

Osstrupen Bridge is a prestressed concrete box girder bridge built by the cantilever construction method. It is 258 meters long and has a single span of 198 meters with a hinge at the central joint. The hinge transfers shear and torsion, allows for axial movements and hence the bridge can be considered as a statically determinate construction. It is built with a varying cross section where the lowest height is 2.46 meters and the tallest is 11.55 meters. To reduce weight there is a 20-meter-long opening in the bottom slab on each side of the hinge. The bridge is anchored with 30-meter-long abutment on each side of the span, they are rock-filled and rock-anchored to counterbalance the weight of the cantilever arms.

Due to the low traffic load on the country road where it is located the deck width is only 6 meters wide, but still wide enough for two light vehicles to pass at reduced speed.

5.2.1 Hinge vs no hinge

The main benefit of designing a cantilever bridge with a hinge in the central joint is that it makes the structural analysis and design less complex. On the other hand, the hinge incapacitates moment redistribution resulting in lower loading capacity compared to a continuous bridge. In addition, the hinge is subjected to various problems and is costly to maintain. Lastly, since the hinge is less binding, deformations can occur due to creep of the concrete. This was the situation on Osstrupen bridge. At the hinge there was a discontinuity between the angle of the cantilever arms due to the large deflection, making it clearly noticeable when passing, leading to concern by the public [49].

5.3 The support structure of Osstrupen Bridge

Cantilever bridges are expected to sag, but Osstrupen bridge sagged beyond what was accounted for, an approximate of 250 mm more than precambered. In addition, the recent deflection rate was larger than what the analysis projected, making it difficult to predict future development [50]. Chloride samples was collected from the bridge, and they confirmed healthy web conditions despite both the age of the bridge and the fact that it is located close to seawater. The analysis of the deck however provided values above warning level, most likely due to the increased use of salt de-icing. The discontinuity at the hinge could be felt as one drove over it causing public concern. The slab in the bottom plate also makes the bridge vulnerable to deflections, so it was sought to find a way to raise and strengthen the girder to comply with the traffic load regulations of 2018. In addition, not only the weight of the support system itself needed to be added to the equation of the sought solution, but also the weight of a new wearing course to fix the deck. [49].

Different concepts to solve this challenge was evaluated, and the one proposed by Aas-Jakobsen, with tensioned steel arches was found to be the best alternative. It was chosen considering the immediate uplift and also preservation of the uplift over time that it would provide [50]. In short, the concept was to add a secondary support system to the bridge consisting of arches. A loading diagram of the chosen solution can be seen in Figure 8. By jacking these arches, that were connected to the bridge with a number of frames, seen in Figure 9, that had a certain spacing, the uplifting forces would be transferred to the bridge. The arches could be mounted in different ways, however the bottom slab allowed for the structure to be mounted inside the box of the bridge. This meant that the bridge could be fixed without altering the appearance of it, so this solution was chosen [49].

The engineering project was carried out in cooperation between the Norwegian Public Roads Administration, the engineering consultation company Johs Holt AS, and FiReCo an engineering partner for structural design. Contractor for the project was NCC [51].

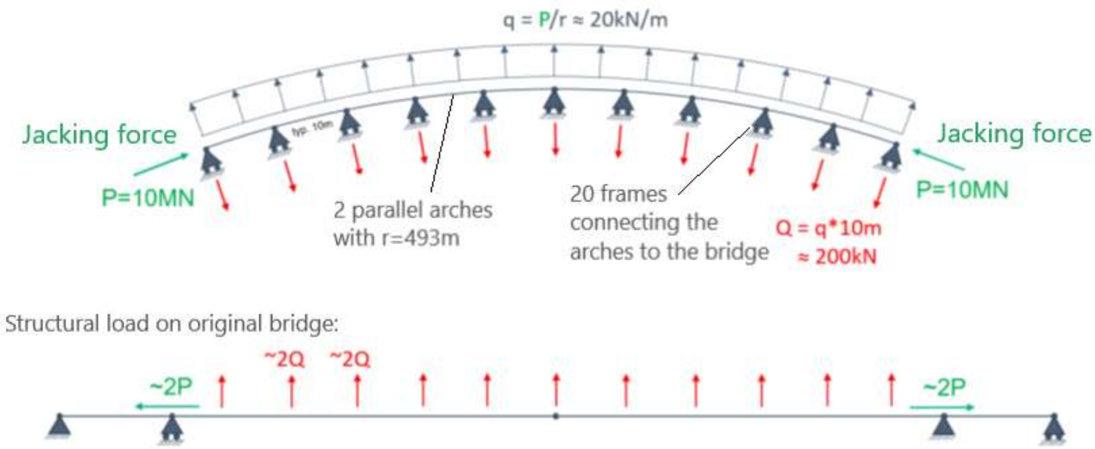


Figure 8: Loading Diagram[4]

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[4] Source: [51] J. Holt. *Forsterkning og Rehabilitering av Osstrupen Bru.* (2020). nvfnorden.org. [Online]. Available: https://nvfnorden.org/wp-content/uploads/2020/06/Island_Osstrupen-bru.pdf

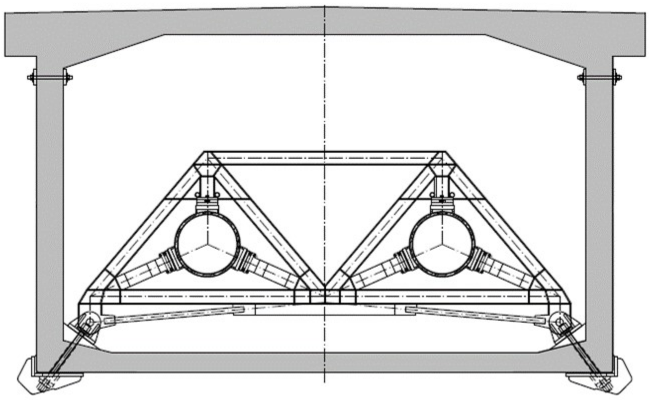


Figure 9: Support structure for the Osstrupen bridge - Frames

The as-built 2D-drawing includes measurement data from levelling bolts mounted in pairs on both sides of the upper edge of the bridge with approximately equal spacing all across the length of the bridge. This is done in accordance with chapter 7.2.9 in the handbook N400 [2]. The required accuracy of the measurements is specified on the drawings to be +/- 2mm. The bolts are used to keep track of the deflection of the bridge. The levelling bolts were measured at different times during the construction of the support structure. Figure 10 shows the deflections, the green graph is showing the difference in the measurements between the start of the project, January 2018 and right before jacking, November 2018. The large deflection is caused by the weight of the structure being mounted onto the bridge.

The light blue graph in Figure 10 illustrates the uplift that was achieved from jacking the arches, with the extra deflection caused from the weight of the support structure accounted for. The goal of the project was actually to have more uplift than what was achieved. However, it was concluded that the large platform that was used to load the steel parts into the cavity of the bridge, seen in Figure 11, subjected the bridge to a permanent deflection [50]. Lastly, the dark blue graph shows the deflection after the new wearing course was added to the deck.

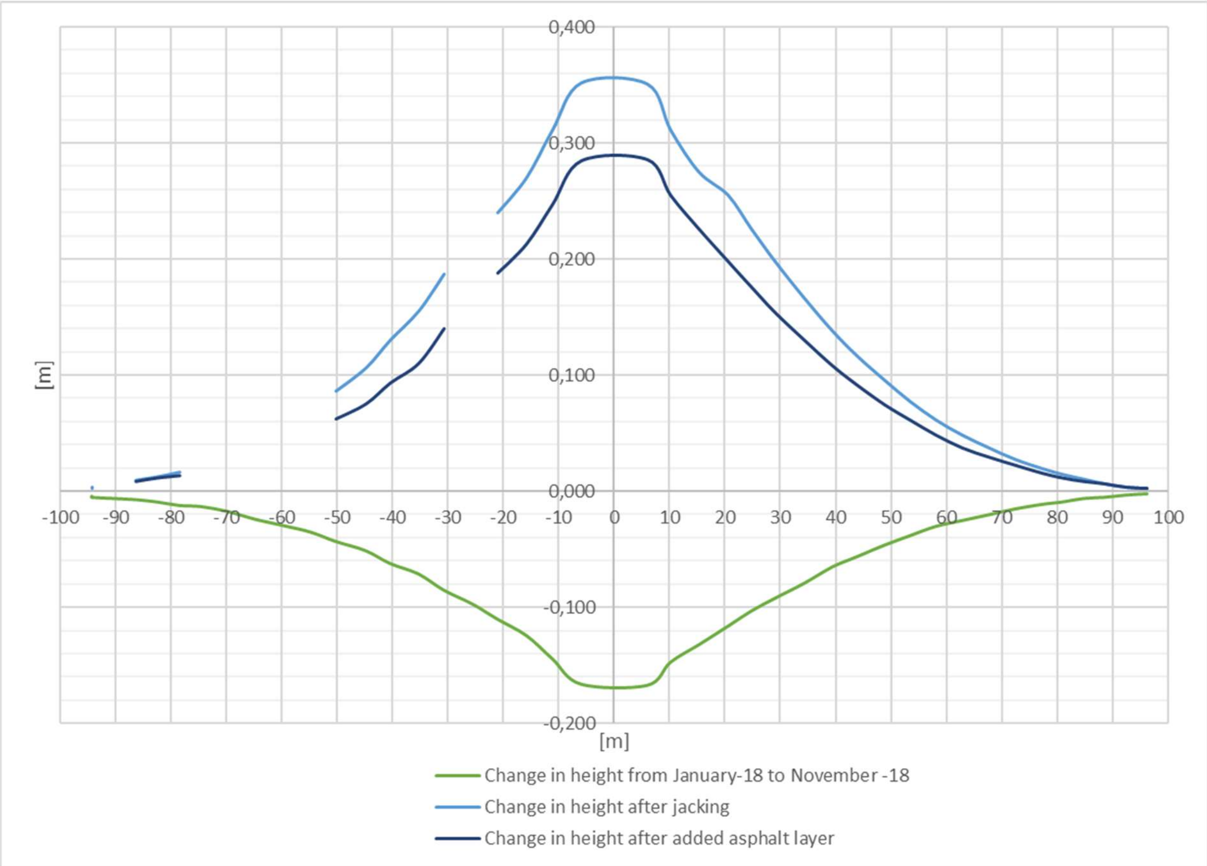


Figure 10: Deflections of the bridge during the construction of the support structure

Figure 11: Bridge with added platform at the hinge where all the parts of the support system were inserted[5]

5.3.1 Design

An extensive analysis was carried out to evaluate two different material options for the arches, carbon fiber and steel. The report concluded with carbon fiber being the best option, due to the lower density allowing more uplift to the bridge [52]. The carbon fiber option was estimated to approximately 56 tonnes and the steel option was estimated to approximately 144 tonnes [53]. Furthermore, carbon fiber has a lower thermal expansion coefficient ($1.8 * 10^{-6}\,°C^{-1}$) than steel ($1.2 * 10^{-5}\,°C^{-1}$) thus resulting in lower load effects due to changes in temperature. However, there were no suppliers that bid to deliver this option, even with a sufficient price reduction included, so the solution with steel arches was chosen [49, 50, 52].

The analysis (performed before support structure was added) also concluded that the bridge would ultimately classify according to NPRA's loading requirement named "Bk 10/60" where the 10 refers the axial load of 10 tonne (100kN) and the 60 refers to the maximum total weight of 60 tonne (600kN) [2, 52, 54].

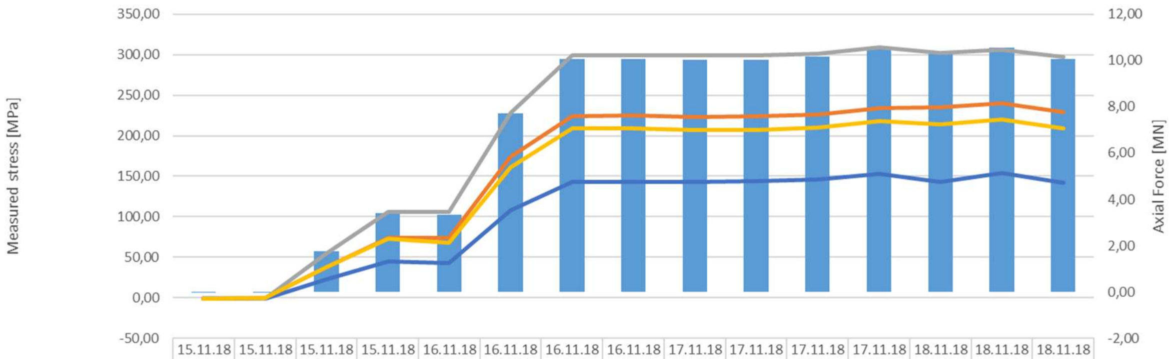
[5] Liv Standal, Firdaposten

5.3.2 Monitoring

The monitoring of the arches is done utilizing Fiber Bragg Sensors installed by the company Light Structures AS. The main reason for adding sensors to the support structure was to monitor it during the critical jacking process. After the jacking was completed, the sensors provided online reporting with a monthly follow-up. In total there are more than 200 sensors mounted on the steel structure. There were two sensor schemes set up, one for the arches and one for the frames.

However, the sensors on the frames generated data of poor quality. This was partly due to an unfortunate placement of the sensors, as they were mounted close to the interface of the arch in which the area is sensitive to stress concentration and uncertain boundary conditions. In addition, the placement of the sensors was carried out with low precision [50]. Fortunately, the sensors mounted on the arches functioned effectively. In this thesis, only the sensors on the arch will be discussed and taken into consideration.

The monitoring started 15th of November 2018, which was the day the jacking started. Figure 12 is the sensor output from the sensors mounted on the arches close to the hinge (see Figure 14 and Figure 15 for description of the sensor notations). Based on the sensor output the jacking started in the morning the 15th of November, stopped during the night, and continued the next day. By 12 o'clock the jacking may have finished based on the measurements stabilising.



	15.11.18 00:00	15.11.18 06:00	15.11.18 12:00	15.11.18 18:00	16.11.18 00:00	16.11.18 06:00	16.11.18 12:00	16.11.18 18:00	17.11.18 00:00	17.11.18 06:00	17.11.18 12:00	17.11.18 18:00	18.11.18 00:00	18.11.18 06:00	18.11.18 12:00
PW S00 Axial Force	-0,04	-0,04	1,75	3,42	3,33	7,70	10,06	10,07	10,02	10,04	10,16	10,52	10,27	10,57	10,07
PW S00kl12	-0,96	-1,66	22,39	44,84	42,29	107,92	143,31	142,96	142,53	143,55	145,96	153,40	143,15	153,72	141,70
PW S00kl9	-1,00	-0,18	37,42	73,77	73,52	173,81	224,54	225,30	223,58	223,87	226,49	234,07	235,02	240,28	229,34
PW S00kl6	-0,03	-1,00	54,44	106,19	105,75	228,21	299,43	299,51	299,05	298,90	301,73	309,65	302,07	306,44	297,00
PW S00kl3	-1,19	-0,42	37,96	72,68	68,13	160,76	208,82	208,63	207,39	207,24	210,27	218,25	213,60	219,66	208,95

Figure 12: Sensor output during jacking of support structure

Chapter 6

Digital 3D Model

The digital twin requires a digital model to use for visualising the structure, much like BIM. If a BIM model exists, this can be used as a basis. For existing bridges, a BIM model is often not available, most likely no digital model whatsoever. Thus, a digital 3D model needs to be created. For older bridges the original 2D drawings, if still available, might not represent the structure to an optimal degree. Bridges suffer from deterioration mechanisms that also affects the structural behaviour of the bridge. For the analysis to reach adequate results the structure needs to have a digital model that represents the actual state of the bridge.

In this thesis the bridge and the added support structure has been modelled based on the as-built drawings that was created after the support structure was mounted. In addition, a 3D scanning was conducted of the support structure in the cavity of the bridge. These scans were used as a guide to create a model of the structure. As the objective of this thesis was to look at the stress measurements from the arches in the support structure, a scan of the bridge's loadbearing structure was not conducted.

The preliminary idea for the case study was to scan the support structure inside the bridge, use the generated point cloud to make a 3D model applicable for FE analysis, and to compare the results from the analysis with the data collected from the sensors mounted on the structure. However, some challenges occurred that will be described in more detail below. Basically, the 3D model created from the scans were not applicable for analysis. Consequently, the model based on the drawings were considered for the analysis. The challenge that occurred here was that the author had trouble defining the loads and boundary conditions of the arch to sufficiently represent the system. This was solved by creating the whole bridge (leaving out the abutments on each side) by using shell and beam elements.

Shell and beam elements are often used to reduce the required computational power when a more complex structure is to be analysed. They can be used when the individual object in the structure has a dimension, like the thickness of a wall or the cross-section of a beam, that is significantly smaller than the others. In this thesis the objective was merely to analyse the digital structure once, and then compare the results with the data obtained from the sensors. However, in the case of a digital twin, where the analysis is proceeding close to real-time. A model of this type will efficiently reduce the required time for the analysis to render.

Beam theory is the one-dimensional approximation of a three-dimensional continuum. The reduction in dimensionality is a direct result of the slenderness assumptions, which is: the dimensions of the cross section are small compared to the typical dimensions along the axis of the beam. In Abaqus a beam element is a one-dimensional line element in three-dimensional space or in the X-Y plane that has a stiffness associated with deformation of the line (the beam's "axis"). These deformations consist of axial stretch; curvature change (bending); and, in space, torsion. A key issue in using beam elements is to judge whether such one-dimensional modelling is appropriate. The fundamental assumption used is that the beam section cannot deform in its own plane.

6.1 Definitions

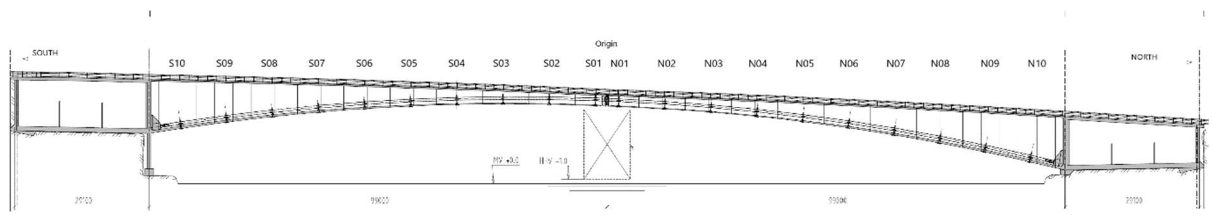


Figure 13: 2D Drawing of the bridge with frame and arches installed

6.1.1 Arch notation

There is two arches and they have been assigned the notations W for the arch situated west of the origin, and E for the arch situated east of the origin.

6.1.2 Frame notation

Referring to Figure 13 the different arches and all frames have a notation that reflects their placement relevant to the origin which is defined to be in the middle of the hinge. The letter notates if the frame is situated in north- or south-direction relevant to the origin. The number counts the frames, 1 to 10, starting from the origin in both directions.

6.2.3 Sensor notation

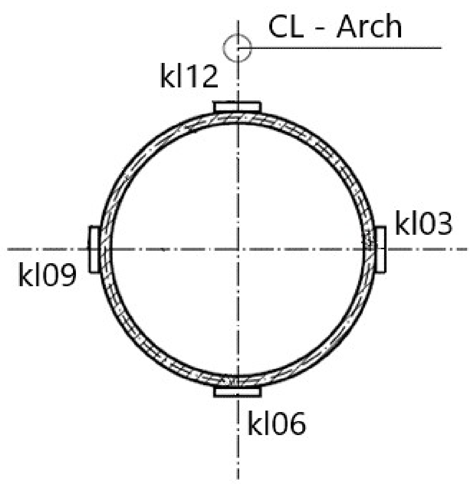


Figure 14: Notation of Sensor positions

Figure 14 illustrates the notations of the sensor positions on the arches cross section. There are sensors mounted on both the west and the east arch, and they are situated near frame 10 on both sides, near frame 5 on both sides and near the origin. See Figure 15 where the red x-es mark where the sensors are situated.

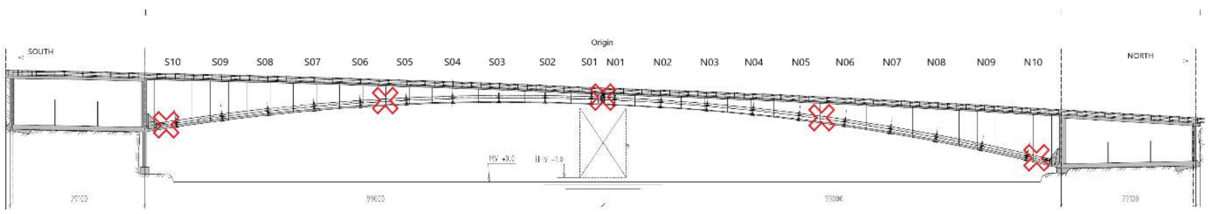


Figure 15: Sensor positions on the arches

Given the above descriptions, the sensor notation can look like this:

W S05kl06

And should be read like the following:

W – west arch

S – south of the origin

05 – near to frame number 5

Kl06 – sensor at position kl06 (see Figure 14)

6.2 The model based on drawings

The arches were modelled, in Abaqus, according to the as built 2D drawings that was produced after the mounting of the support structure. The drawings are dated 19.06.2019 and are marked "As Built" according to the Norwegian Public Roads Administration' Handbook N400 [2] chapter 1.4.8, drawings shall be provided when the construction is complete. The frames were left out as they would be very time consuming to model in detail, and they can be replaced by boundary conditions or as rigid beam elements in the analysis.

The drawings show the construction post-jacking, so the initial deflection around the hinge pre-jacking is not accounted for in this model. If, in the future, an analysis of the jacking process is to be carried out, the deflection needs to be added to the model.

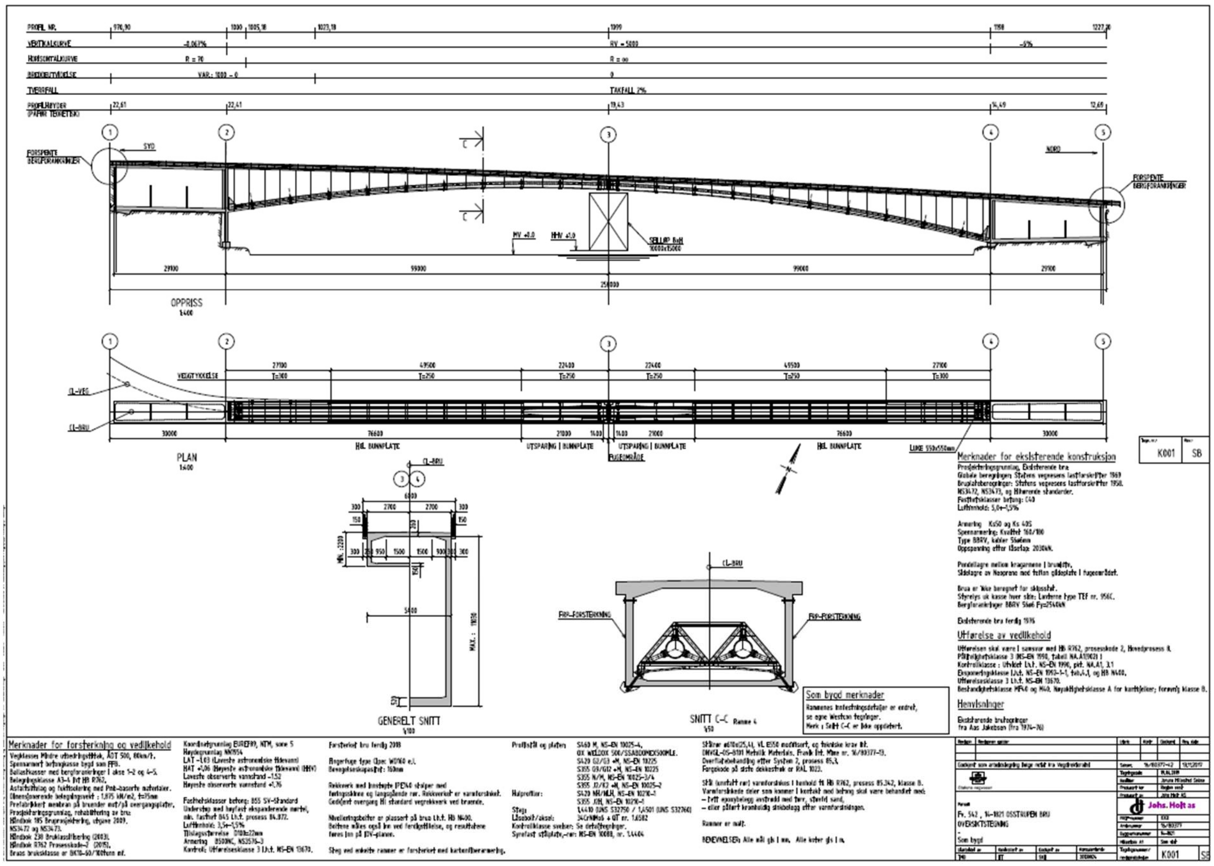


Figure 16: As built 2D drawing of the bridge with support structure

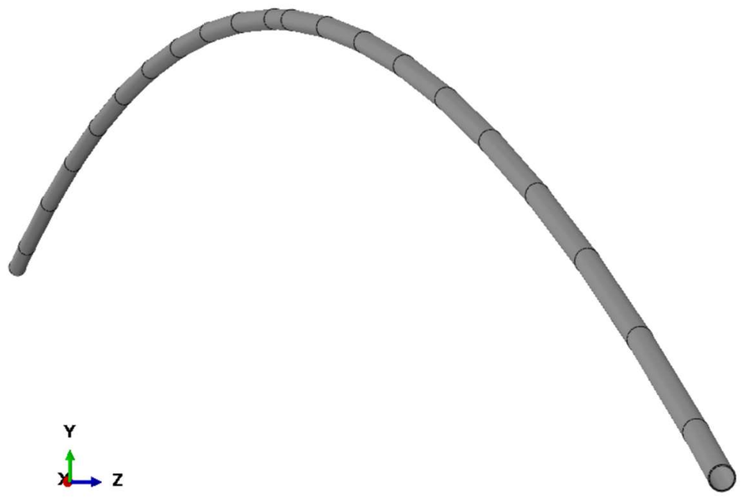


Figure 17: Arch modelled based on the as built drawings

6.3 Based on 3D scanning

A 3D scan of the steel structure was executed to capture the real geometry. The sensors are all installed on the steel structure, so a scan of the bridge itself was not prioritized. In addition, due to the geometry of the bridge and for safety precautions, a scan from the deck was not conducted as there is no sidewalk. Depending on the use of digital twin a scan of the concrete structure would be considered beneficial, but with no sensor data from this part of the bridge it did not seem vital for this project.

6.3.1 3D scanning process

In this chapter the process from scanning to a 3D model that was chosen for this project will be described.

Figure 18 illustrates the steps taken in the case study of this thesis, with the chosen software listed under the step. Each step will be described further in the following subchapters. The software's that have been used were selected based both on accessibility and on the different software knowledge-level of the author.

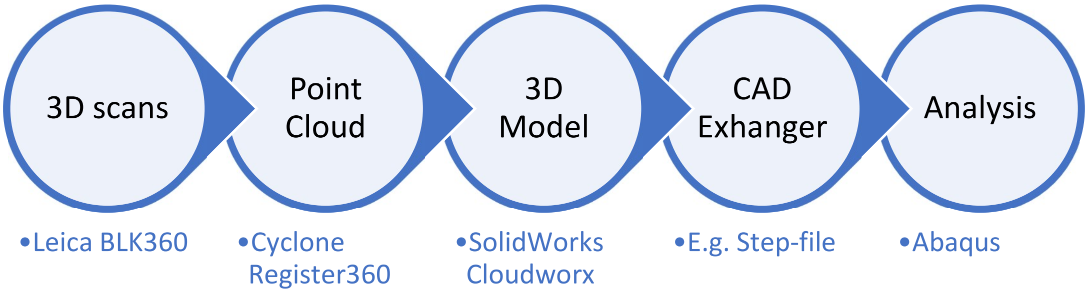


Figure 18: Process from 3D scanning to analysis

6.3.2 Leica 360BLK

Leica BLK360 is a 3D scanner with integrated spherical imaging system and thermography panorama sensor system. The spherical imaging system consist of mathematical equations that deforms a spherical image so that it can be displayed on a 2-dimensional screen. The scanners height is 16,5 cm and it has a diameter of 10 cm, and it weighs 1 kg. It can be operated with a single button, or it can be remote operated with an iPad application. Its ranging accuracy is 4mm at 10m and 7mm at 20m. The user can choose between three resolution settings: high, medium and low. [55] The scanning process for an image with low density takes approximately 40 seconds, the medium option takes about 1 minute and 30 seconds to scan. It was assumed that the required quality of the point cloud would be sufficient with a mix of low and medium scans, so the high option was not used in this project.

The bridge has an opening in the north end where one can access the cavity of the bridge. For safety reasons, it was decided that two operators should carry out the task. The chosen scanner, with its small size and light weight was a good option for this assignment, as it could be safely carried in a regular backpack whilst the operators climbed into the bridge cavity, and also over and under the arches throughout the cavity. Figure 19 shows the scanner in action. The scanner does not require to be levelled prior to scanning. However, due to the steep alignment of the bottom deck a dust tray, as can be seen in the figure, was used to adjust the scanner closer to a horizontal level.

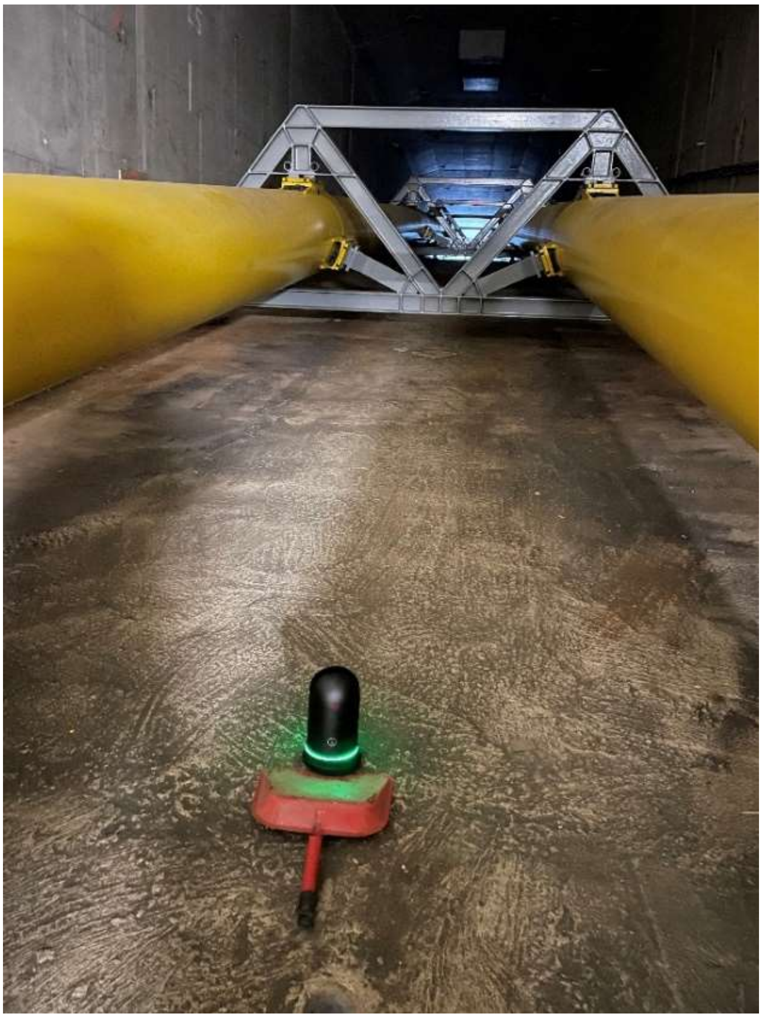


Figure 19: Leica BLK360 during scanning

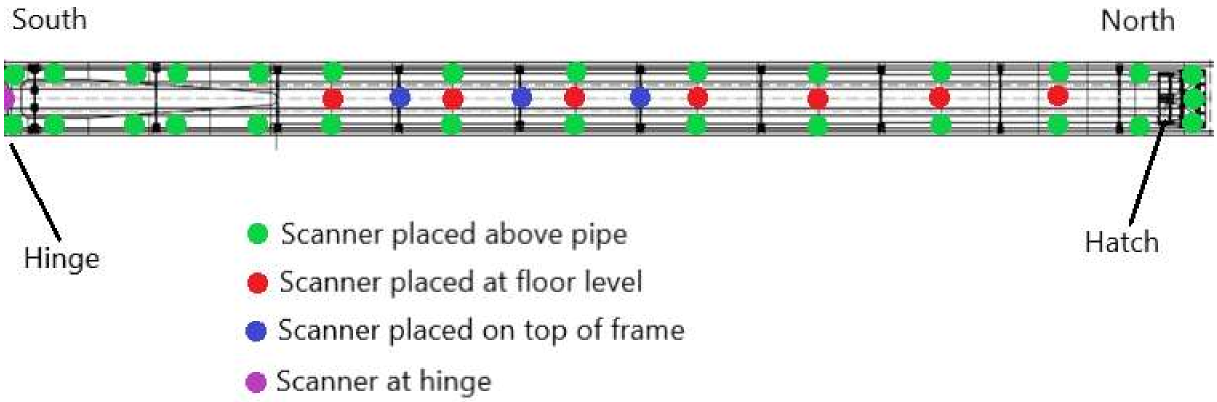


Figure 20: Scanning position layout

It took 79 scans in total, Figure 20 shows the positions of the scanner throughout the cavity of the bridge, the scanning is symmetric over the hinge so only half of the bridge is illustrated on the figure. The placements were done in a mesh denser than what is required by the scanner's specification. This was done as a precaution, as there would be no possibility to go back and re-scan. The relatively small space available between the concrete and the steel arches also was a factor that supported a high density of the scans as the steel construction was the main target for the scan. When the scanner is placed too close to the target it cannot capture the surface. This led to missing surface information in the area close to the placement of the scanner, see Figure 21. To capture as much of the geometry as possible it was concluded that there was a need for scanning on both sides of the structure and in between the arches. In addition, the height was alternated between above the arch and below the arches (green and red dots on Figure 20). Some scans were also taken from on top of the frames (the blue dots on Figure 20). These were done with the medium resolution setting, which compared to scans with low setting resulted in more detail and noticeably less missing geometry.

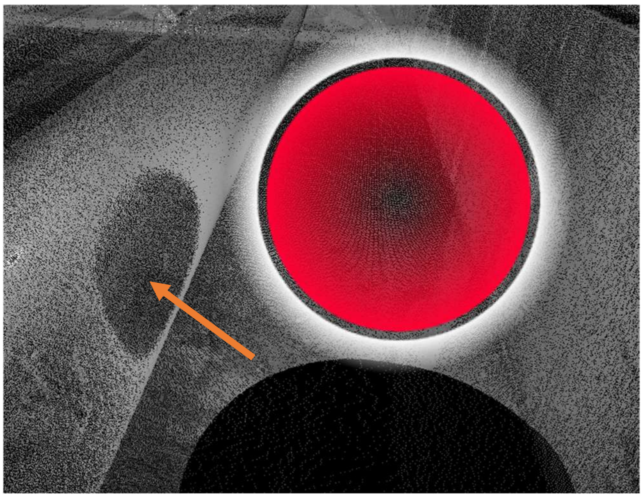


Figure 21: Missing geometry on arch due to placement of scanner

One scan failed to upload for unknown reasons. However, due to the scans being executed with sufficient overlap, the missing scan did not cause any major set-back.

6.3.3 Register 360

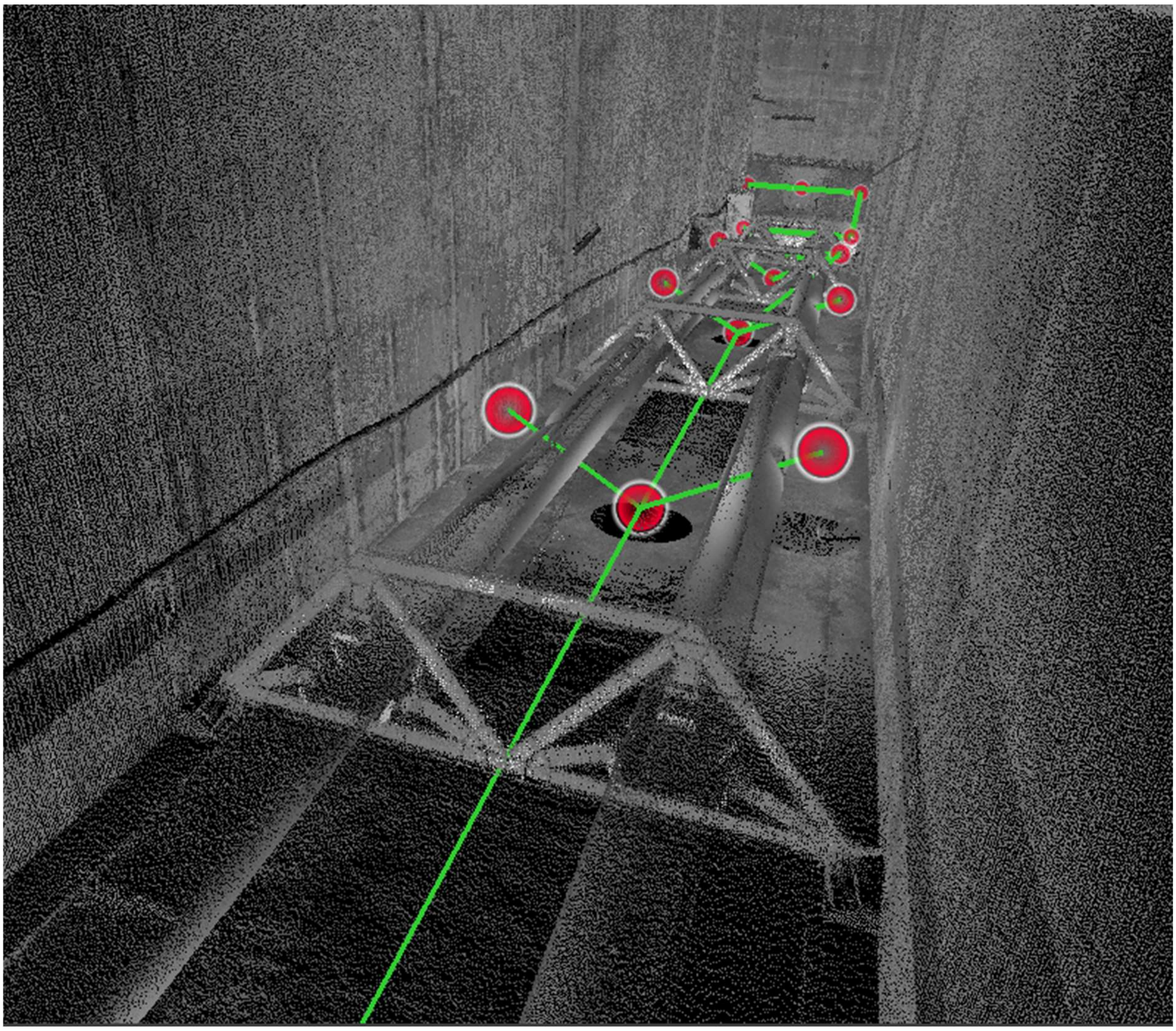


Figure 22: Individual scans (red) are linked (green) in Register360 to form one total point cloud of the construction

The scanning resulted in 79 individual scans. To assure the process of connecting the scans it is a good rule to try to make sure that approximately 50% of the scans overlap. Connecting the scans can be efficiently done in Register 360. The program automatically suggest links if it has many enough points that overlap. But it is advised to go through the links to see if they are accurate. The links can be adjusted in orientation and height accordingly to better correspond to each other. See Figure 22 for an illustration of a linked point cloud. The red dots in Figure 22 is where the scanner was positioned, and the green lines illustrates the links that have been created between the scans. The finished product is a single point cloud that can be saved into multiple different file types e.g., *LGS or *E57.

The point cloud consists of points from the surface of all the geometry surrounding the scanner, e.g., walls, ceiling, and floor. To make the modelling of the arches easier the irrelevant geometry was cut out of the point cloud, only the points capturing the geometry of the arches and the frames were kept. See Figure 23 for the finished result, with Figure 24 showing a close-up of the arch and frame.

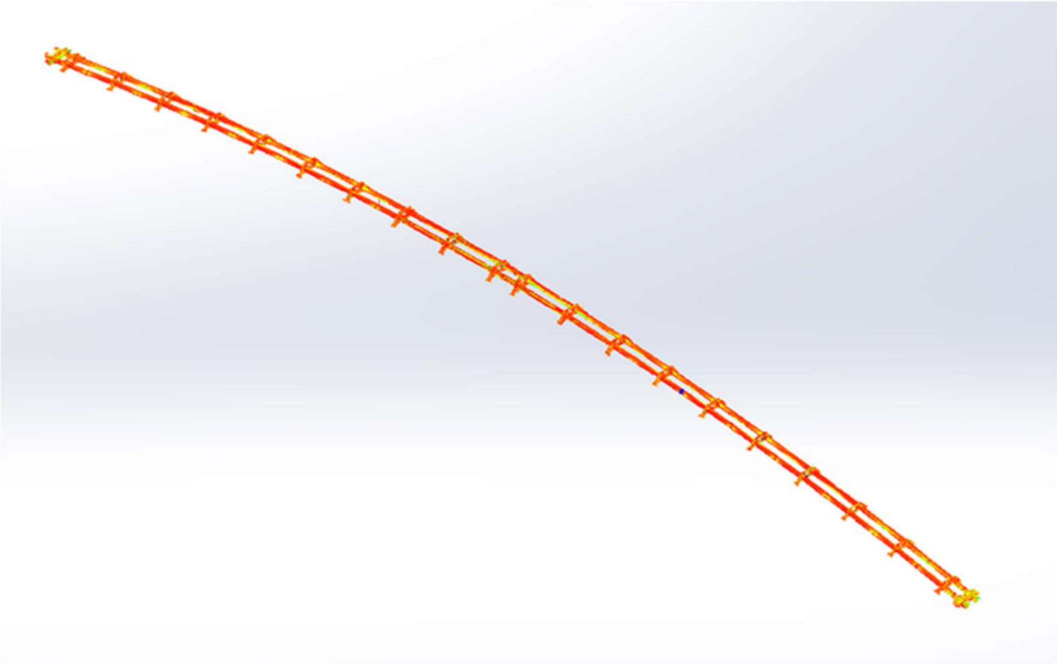


Figure 23: The point cloud has been cleared out of surrounding geometry

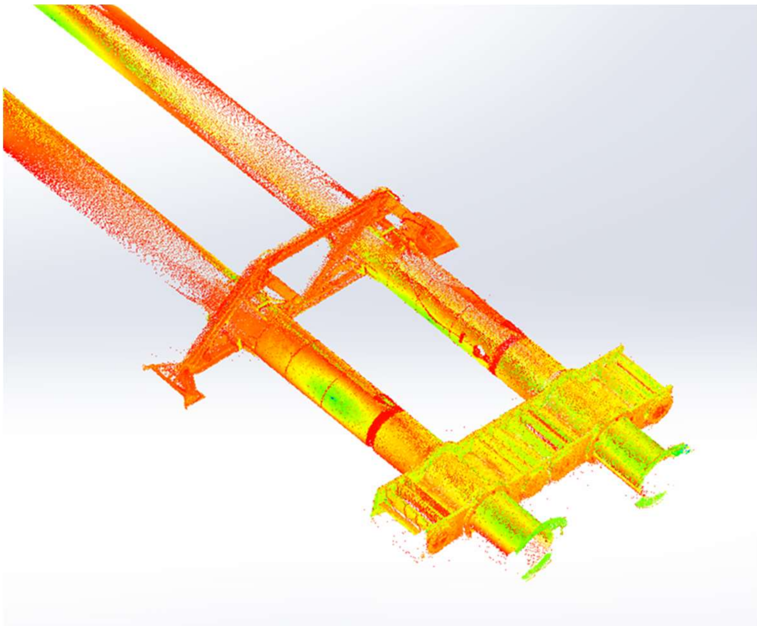


Figure 24: A close up of the point cloud of the arches and the frames to illustrate the detailing level.

6.3.5 SolidWorks Cloudworx

The process of modelling based on the point cloud was done using Leica CloudWorx Digital Reality, which is a plug-in program for SolidWorks and a selection of other CAD systems (at the time of writing, there is no plug-in from this software available for Abaqus). The program can recognize specific features in the point cloud, e.g., arches and beams and the user can generate these geometries rapidly with only a few clicks. The program has built in catalogues for standardized piping and beam sizes, and it suggests the standardized size based on the selected geometry. Unfortunately, for the case of the arches there were challenges with this feature of the program. The arches in between the frames were generated with no issue but linking two arches together which in this case has an angle of below 1° seemed to be a task that this software simply was not designed to do. The result had several discontinuities in the surface, see Figure 25. Firstly, this makes the model not a good representation of the physical structure. Secondly, it's not suitable for FE analysis. An effort was made to try to fix the geometry, but it was concluded that to improve the model manually would be too time-consuming for the scope of this thesis. It is assumed that the very small angle between the arches was the reason for the discontinuities; the algorithm in the software may be tuned to connect arches with larger angles, e.g., 45° or 90°, which is more often the situation in piping systems which the algorithm is designed to tackle. It cannot be ruled out that the authors lack of experience with the program could also be a source of error.

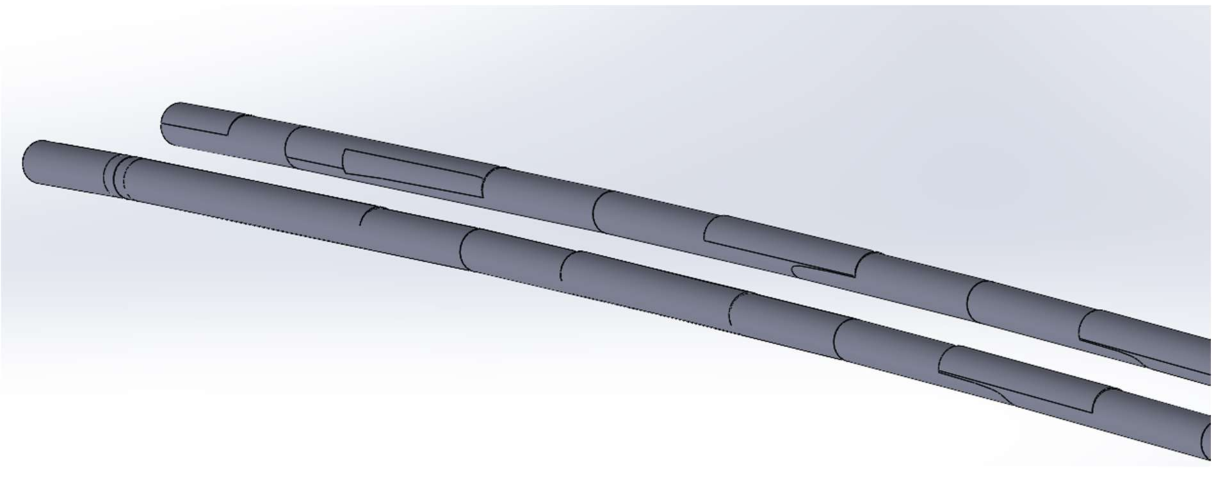


Figure 25: The arches modelled based on the point cloud using the Cloud Worx plug-in software in SolidWorks.

6.4 Comparing the models

To accommodate the challenge described over, a single arch was modelled in Abaqus based on the 2D-drawing, and this was compared with the point cloud to identify discrepancies. This was done by adding them into SolidWorks as an assembly. It was found that locating the arches in accordance with each other to perform a visual comparison was challenging due to missing reference points. By bringing back the surrounding geometry, e.g., walls etc., it was easier to manually position the arches relative to one another, as the geometry provided a visual guide.

The north part of the arch was made concentric with the position of the point cloud close to the jacking console. This had to be done visually as mentioned above, as there was no way to reference the 3D-model to the point cloud. The model was positioned parallel to the x-axis of the point cloud (the length). When the model was positioned accordingly, a small displacement could be observed as illustrated in Figure 26 and Figure 27. It was not straight forward how to determine the correct cause for the displacement as this could stem from a small difference in angle between arches anywhere along the arch. The displacement could not be measured in the software. However, it was considered to be too small for it to be of relevance to the required accuracy level for this scope. Consequently, the model considered in the continuance of this thesis is based on the 2D drawing with no adjustments added after comparing it with the point cloud from the scans of the physical bridge.

Figure 26: The modelled arch (red) is compared to the point cloud arch

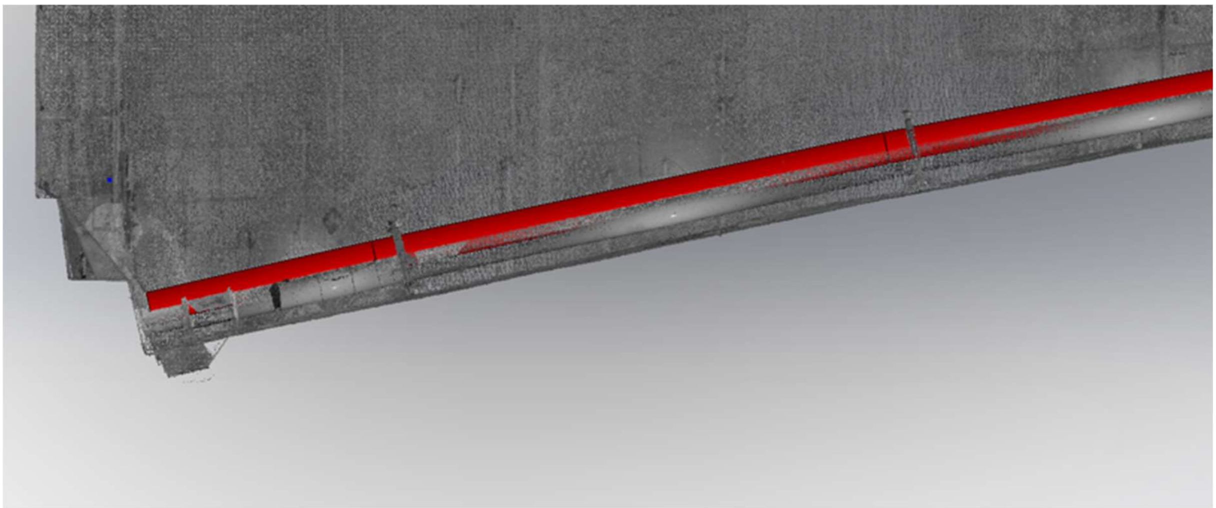


Figure 27: Close-up of the displacement of the south end of the arch, when the north end was positioned concentric with the point cloud arch

It can be assumed that comparing directly with the point cloud, as done here, was the better option for this project. This assumption is based on evaluating the accuracy level needed with the workload it would require modelling the arches. Modelling the geometry based on the point cloud “manually”, meaning without the help of the automated function provided in CloudWorx, would be too time-consuming for the scope of this thesis.

6.5 Arches modelled as solid

The first model of the arches created was modelled as three-dimensional solid element, also called a continuum element. The intent was to do a FE analysis of the part, with the respective loads defined and interfaces added as boundary conditions. The result could then be compared with the sensor data, to evaluate how close to the sensor measurements the digital model could come by this method. To be able to plot the analysed stress at a single point in a model, it needs to be defined as a continuum part. And to sufficiently match the result with the sensor output would require this option. However, defining the loads and the boundary conditions came to be a challenging task. The challenge of defining the interface between the frames and the arches was the most difficult. To avoid stalling the progress further, it was proposed to make a simplified model of the whole bridge with the support structure mounted accordingly. An analysis of this structure could possibly contribute to a broader understanding of the load distributions in the structure, which would make it easier to make a continuum element of the part in question.

6.6 Analysis Model

A simplification of the structure was created to analyse the behaviour of the system using beam and shell elements to reduce the computational time. A beam element is, in Abaqus, a one-dimensional approximation of the three-dimensional continuum, and the reduction in dimensionality is a direct result of slenderness, meaning that the dimensions of the cross-section are small compared to the dimension along the axis of the beam. Similarly, shell elements are used to model structures where one dimension, the thickness, is significantly smaller than the other dimensions.

The concrete parts of the bridge are modelled as shell elements. The thickness of the bottom slab varies throughout the bridge, and there can only be defined one thickness to a shell element. To solve this in a way to reflect the change in geometry, the bottom slab was divided into separate elements between the frame positions. The thickness was then defined as the mean thickness between the edges of the element. This also allowed for the frames to be easily positioned at the edge between two bottom slab elements.

The arches and the frames were modelled as beam elements, the cross-sections are defined for the arches as ø610x25.4 and the beams were simplified to all beams within the truss having the same cross-section, HE140A.

The finished model is seen in Figure 28. Figure 29 is a close-up for better visualizing the connections between the concrete elements, the arches and the frames.

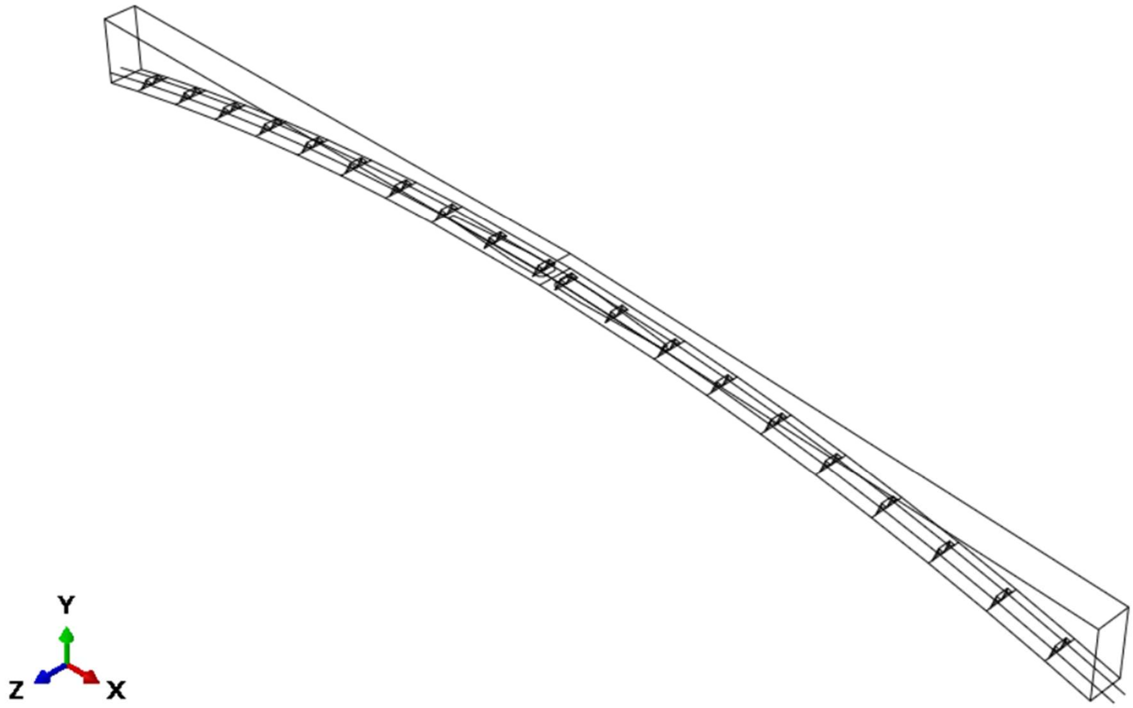


Figure 28: The analysis model assembly

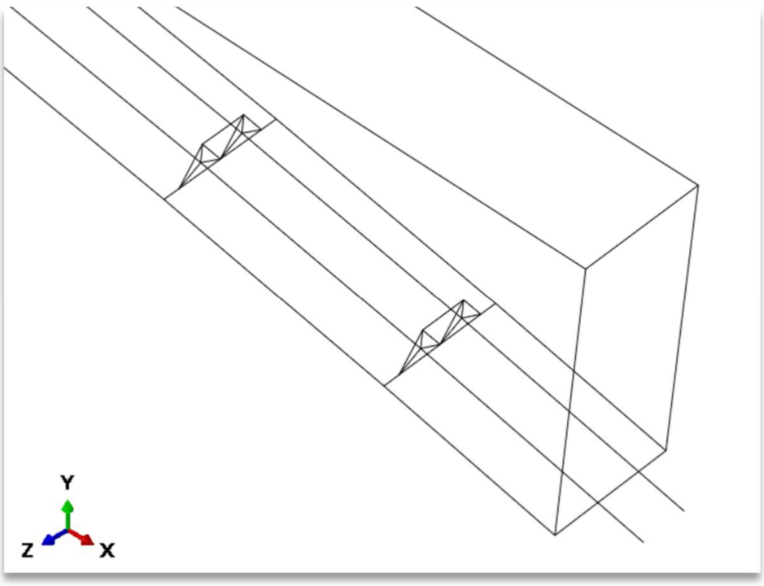


Figure 29: Analysis model close-up

6.6 Analysis

An analysis was carried out to test the credibility of the digital model.

As seen in Figure 30 the short edges are constrained (orange markers), the top edge is constrained in all three directions and the bottom short edges is constrained in the z-direction. The dead load weight (calculated in Appendix B) is added to the structure as a pressure load on the deck (purple arrows). The jacking load is applied to the arches (yellow arrows) with equal force on each arch end, 10MN.

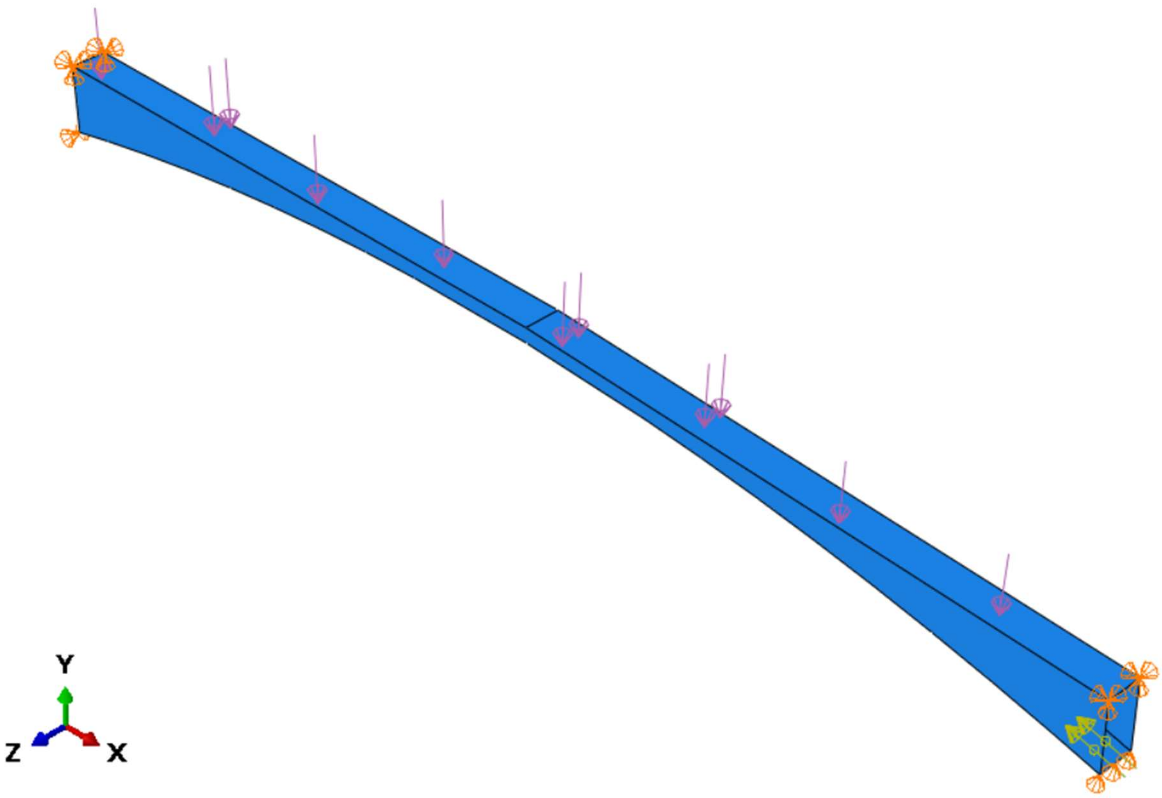


Figure 30: Load and constraints

Figure 31 displays the resulting displacement that was achieved by the analysis, the magnitude is shown in millimetres. Figure 32 displays the von Mises stress attained in the arches by the analysis, the value here is in Mega Pascal.

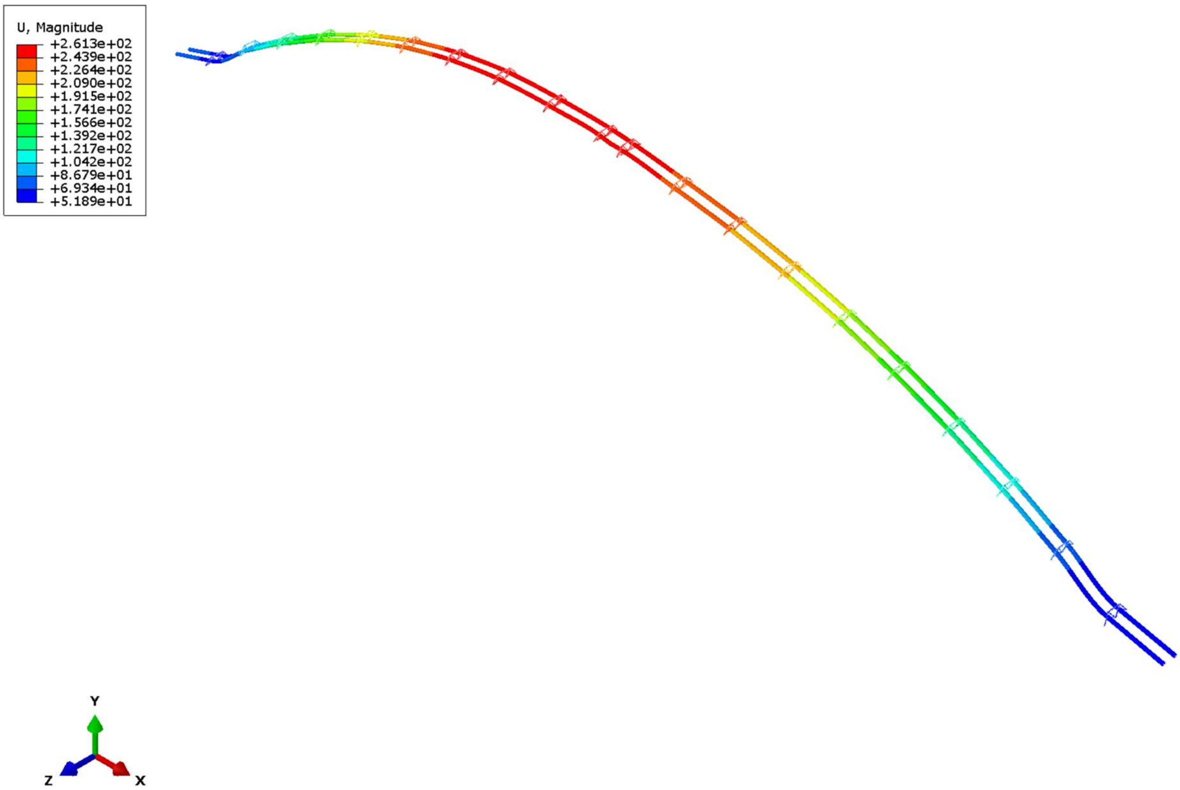


Figure 31: Displacement [mm]

The analysis did proceed as expected. The reason for this is the interface between the arches and frames are defined as fixed in this model. In the physical model they are not fixed due to the functional intent of the structure. Consequently, the 10MN was "absorbed" by the frames, giving them huge deformations. A new analysis was created with the Young's Modulus of the frames increased to avoid the large deformations. The results turned out to make the arches buckle between the two frames closest to the edge, as can be seen in Figure 31and Figure 32. The latter shows the resulting von Mises stress from the analysis, it can be observed how a large amount of the jacking force is utilized in the edges, however still managing to give the bridge uplift.

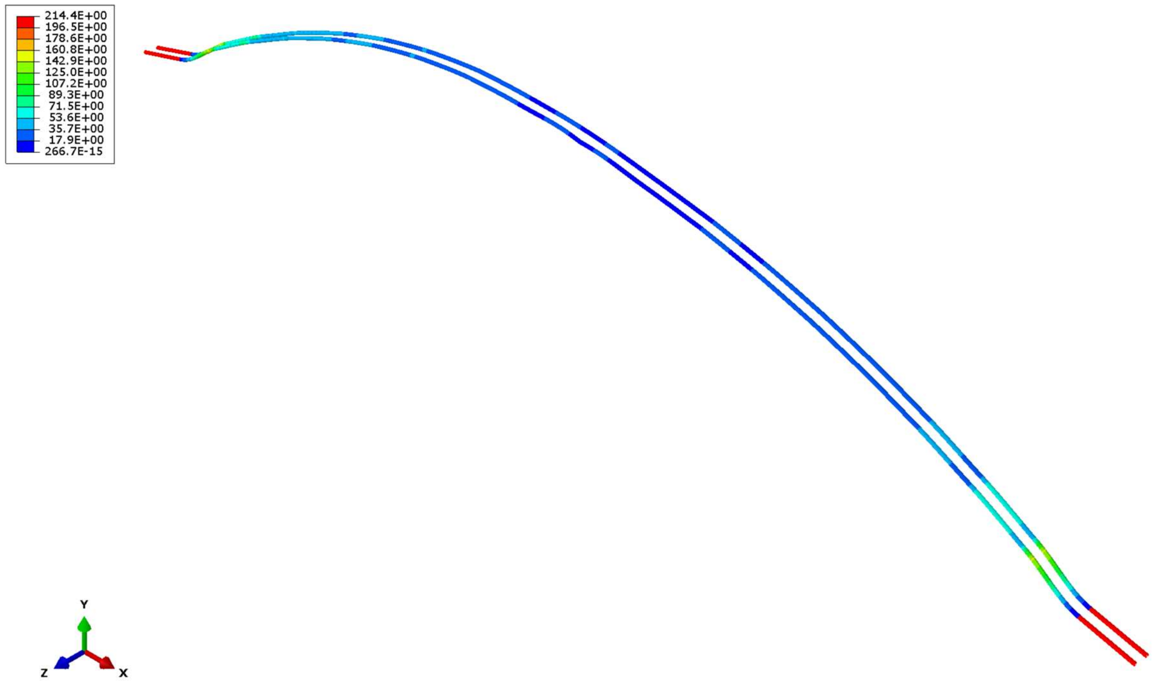


Figure 32: von Mises [MPa]

6.8.1 Parameters for Abaqus

Units

Abaqus is dimensionless consequently this requires the user to manage their use of dimensions in a consistent manner. In Table 3 the units used in this thesis is listed.

Table 3: Units used in Abaqus

Property	Unit
Mass	ton
Length	mm
Time	s
Force	N
Stress	MPa
Energy	N-mm

Materials

Table 4: Material properties

Part	Material	Young's Modulus [MPa]	Poisson's Ratio [-]
Arches	Steel, E550	210000	0.3
Frames	Steel, S420	21000000*	0.15
Bridge	Concrete, C40	26500	0.15

*Young's Modulus for the material used in the frames was set considerably higher than what is realistic for the material – the reason for this is described above.

Chapter 7

Comparison of sensor data with weather statistics

Figure 33: FBG Sensor placed on the arch

During the planning stage of this thesis, it was evaluated that it would be of interest to subject the bridge to a known load, e.g., organizing a truck with a known weight to drive over the bridge. Due to lack of time, this type of experiment could not be conducted. However, another way to evaluate the response of the sensors, seen in Figure 33, would be to compare the sensor history with the recorded wind speed history from the weather station closest to the bridge. This was approved by the supervisors. The Digital Twin concept is defined to be able to analyse and visualize the loads that is being projected to its physical counterpart. Therefore, to identify a fidelity between these two parameters can be seen as a small step in that direction.

Wind effects on a bridge is a complex subject, but a very important one to investigate thoroughly when designing a bridge. Wind load is considered as the most uncertain factor that influences the bridges behaviour. Three common models of bridge vibration under wind effects are vortex-shedding, flutter, and buffeting. Each of these needs to be evaluated during the design phase of the bridge [56]. However, in this context the wind load will be simplified to an assumption of only subjecting the bridge to a dynamic pressure load.

During 3D scanning of the bridge the author experienced the bridge swaying with the wind loads. That day the mean wind speed was recorded by the weather station to be over 20 meters per second, and the wind gusts was as high as 27 meters per second. Qualifying to grade 8, or fresh gale, on the Beaufort Scale, Figure 34.

Beaufort number	Description	Wind speed	Wave height	Sea conditions	Land conditions
8	Gale, fresh gale	34–40 knots 39–46 mph 62–74 km/h 17.2–20.7 m/s	18–25 ft 5.5–7.5 m	Moderately high waves of greater length; edges of crests break into spindrift; foam is blown in well-marked streaks along the direction of the wind	Twigs break off trees; generally impedes progress.

Figure 34: Beaufort Scale

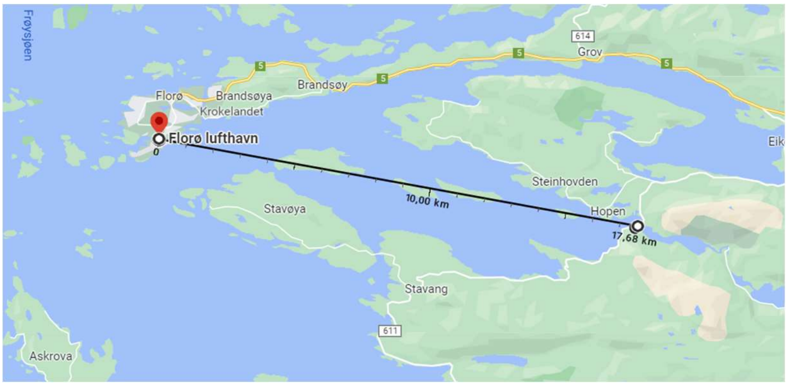


Figure 35:Position of the weather station in relation to Osstrupen Bridge[6]

The weather statistics were all collected from seklima.met.no [57], and the weather station that was found to be closest to Osstrupen bridge was at the Florø Airport. As seen in Figure 35, the distance is 17.68km and it is situated further west on the coast. Figure 36 shows the wind rose for the weather station and this shows that the wind coming from east, or south-east is often of different breeze scales, but when the wind is reaching gale scales the wind direction is more from south or south-west. Considering that the bridge is oriented south-west/north-east some of the strongest wind gusts might not affect the bridge as it will go lengthwise with the bridge, this is assuming that the wind that impacts normal to the side profile of the wind would give the highest load effect on the bridge.

[6] Google Maps

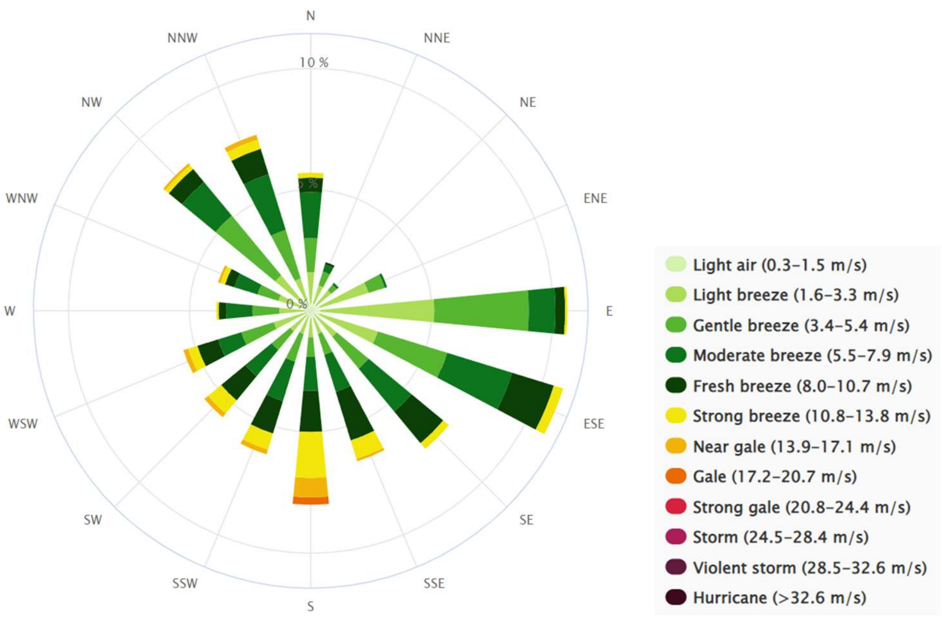


Figure 36: Wind Rose for Florø Airport Weather Station for 2020/2021[7]

Osstrupen bridge is classified with Wind Load Class I according to chapter 2.5.2 of N400 [2]. This classifies the bridge to have insignificant dynamic load effect from wind. Nevertheless, the evaluation was still carried out in lack of other inputs to compare with the sensor data. Other loads e.g., traffic load, snow, etc., there is no way to accurately compare the subjected load to the sensor value as there is no data on the time of loading.

The average temperature was also added to the statistic due to the sensors being sensitive to temperature change as described on page 21. However, the sensors are added to the steel structure mounted inside the cavity of the bridge, and the temperature within the cavity can be assumed not to be directly reflected to the measured outside temperature. It can be assumed that some of the more rapid variations of temperature will be decelerated due to the surrounding concrete. Nevertheless, some assumptions can be made:

- The sensors situated at the hinge (S00) have cut-outs in the concrete on both sides, hence the temperature here can be assumed to be similar to the measured outside temperature
- The sensors situated at S/N05 will experience less of the temperature variations
- The sensors situated at S/N10 will experience least of the temperature variations

[7] Seklima.met.no

7.1 Comparison strategy

Time periods of two separate months were chosen to evaluate the relationship between the parameters; November 2020 and June 2021. The months were chosen after a brief evaluation of a large set of weather statistics and sensor output. It was evaluated if the wind had both rapid changes and periods with relevantly stable wind conditions, as both scenarios possibly could be reflected in the sensor output. Choosing one month from summer/winter season was also a factor due to seasonal temperature differences. Sensor output from two different locations on the arch were gathered, S00 and S05. The wind can cause the long-spanned bridge to sway, and this could possibly be reflected in the standard deviation in the stress measurements from the sensors. Hence, a data sets were collected from the mentioned sensors with data on the standard deviation and in addition the measured stress. A correlation analysis was carried out to get a perception of the linear relationship between the different parameters.

7.2 November 2020

This month was chosen as a sample due to the relative stable first half of the month, then the temperature decreases significantly, and the wind increases accordingly and after a couple of days the situation is more stable again.

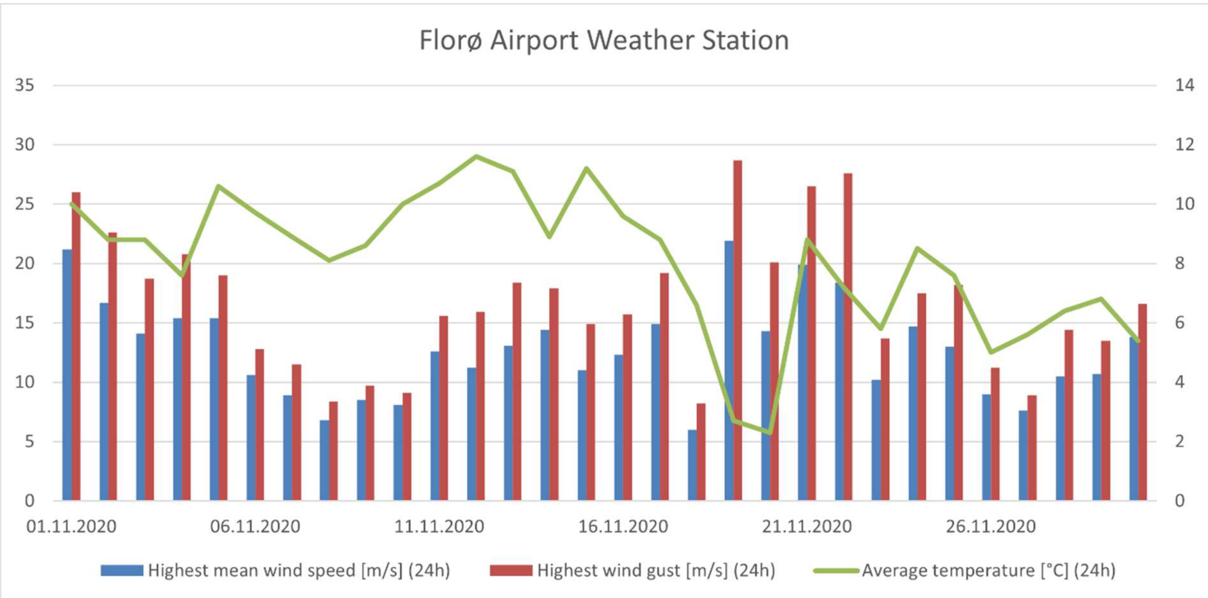


Figure 37: Wind and temperature measurements for November 2020

A slight distinction can be observed in both Figure 38 and Figure 39 around the same time as the unstable weather conditions mentioned above, 18th to 22nd of November. An increase in both measured stress and SD can be seen in the measurements from S05, Figure 39, at the same time there is an increase in the temperature.

However, there is a slight discrepancy between the two graphs below, and that is the increased stress around the 12th – 14th of November. The temperature in this period increases slightly. As assumed earlier the sensor positioned in S00 would experience more temperature vary due to the cut-out in the bottom slab. Hence, sensor S00 in this case is "ventilated", whilst sensor S05 experience warmer conditions due to the surrounding concrete and its high specific heat capacity. The rest of the measurements seem more or less stable.

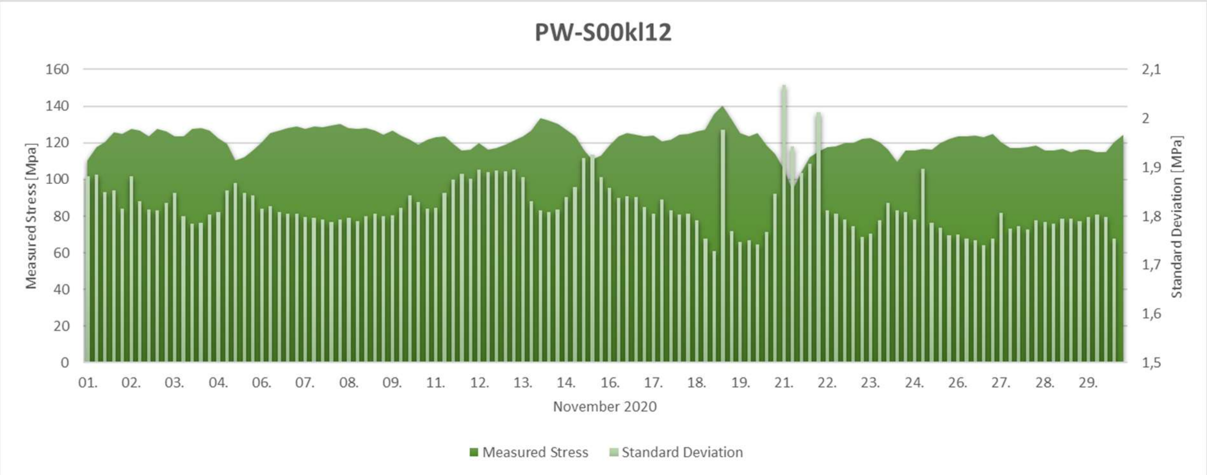


Figure 38: Measurement output from S00 November 2020

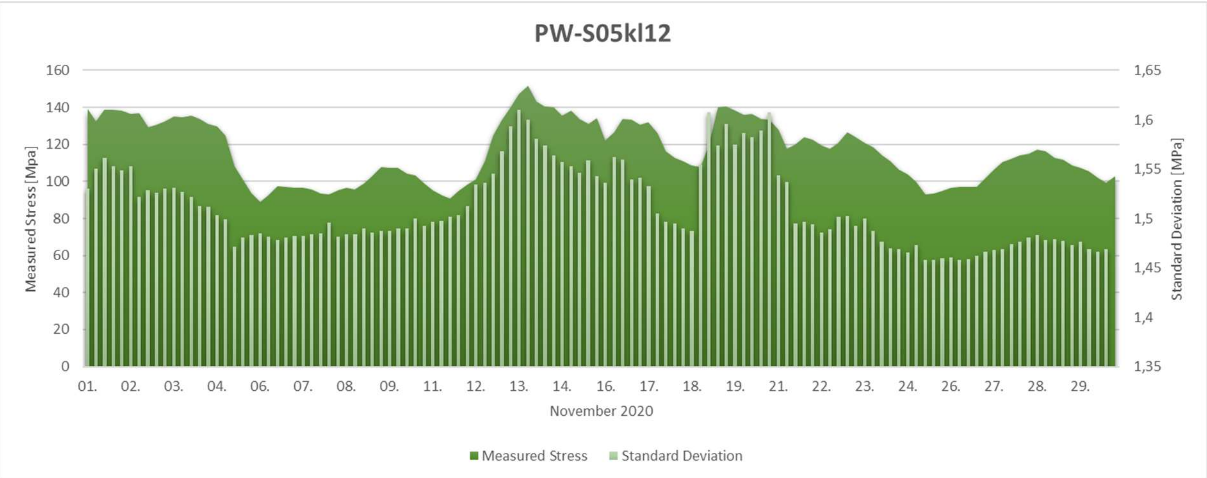


Figure 39: Measurement output from S05 November 2020

7.3 June 2021

Figure 40

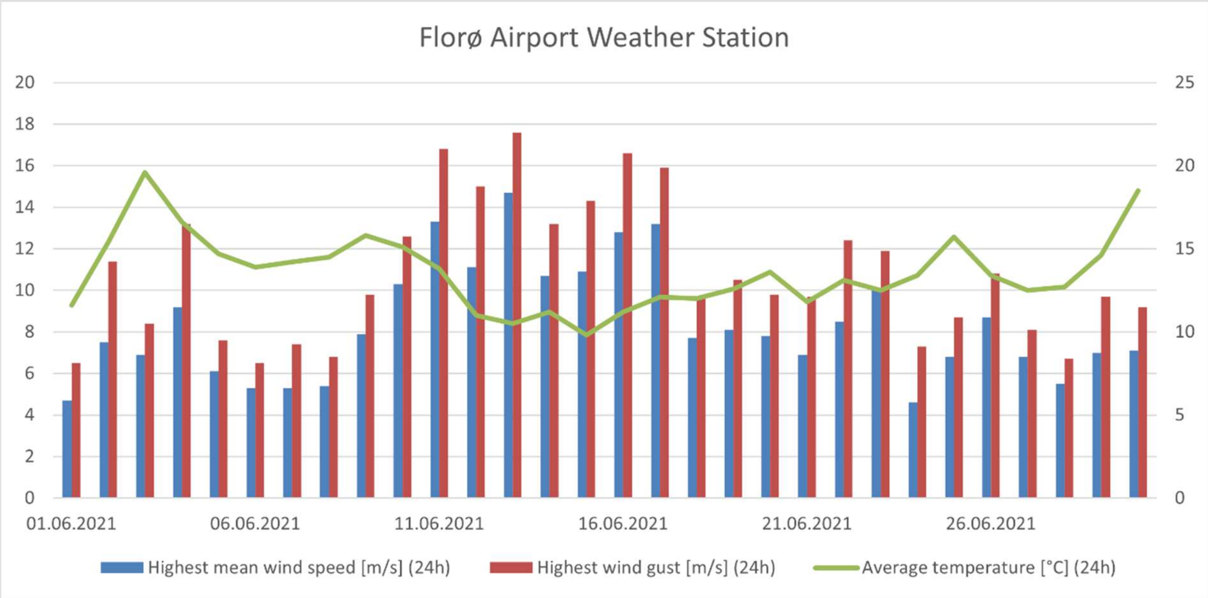


Figure 40: Wind and temperature measurements for June 2021

June 2021 was chosen due to the distinctive higher wind loads from 10th to 17th, see Figure 40. The objective was then to see if the different stress measurements had any difference in their output. Evaluating the graphs in Figure 41, the measured stress seems to pick up the trends of the temperature in the sensor positioned in S00. The SD might pick up the wind in the beginning of the month. And the one high SD measurement around the 9th seems arbitrary, one could speculate if this was the effect of some heavy traffic load.

Measured Stress and Standard Deviation

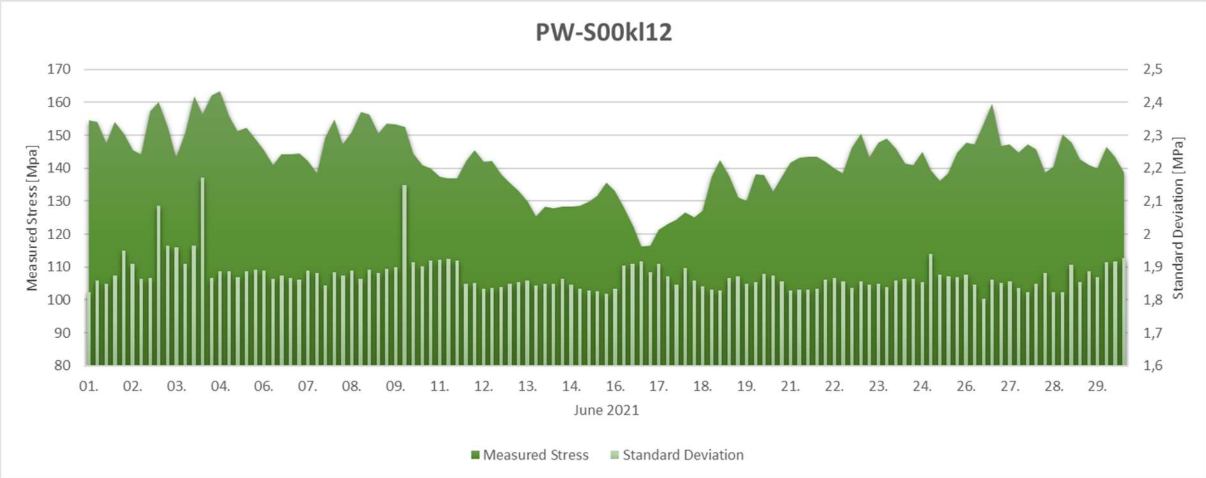


Figure 41: Measurement output from S00 June 2021

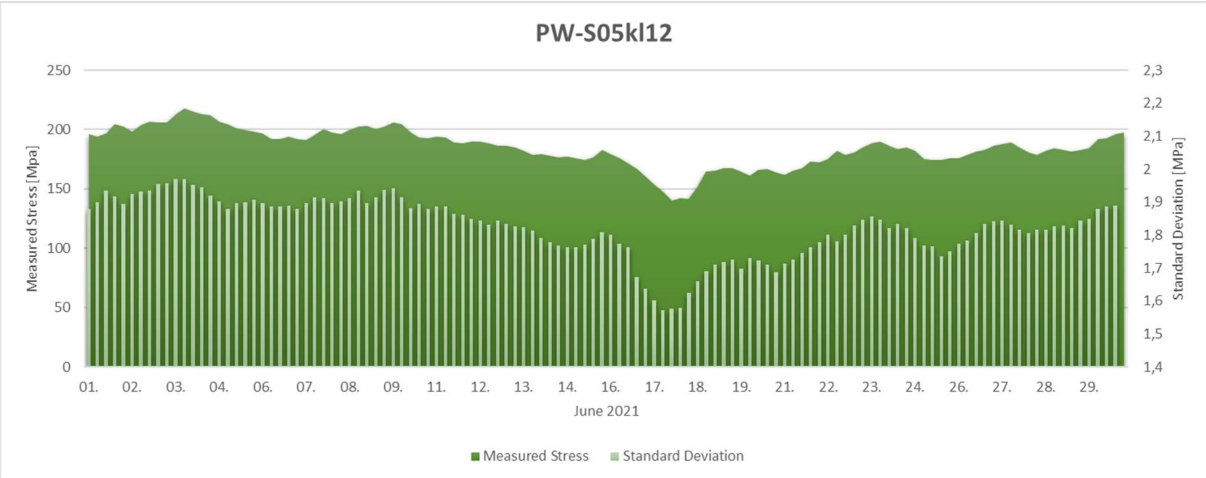


Figure 42: Measurement output from S05 June 2021

In Figure 42 both parameters seem to decrease around the 18th. Comparing to Figure 41 where the measured stress seemed to decrease the 17th. This too could be caused by the specific heat capacity of the concrete surrounding the sensor S05, whilst the sensor S00 experiences more direct affect of the changing temperature.

7.4 Correlation Analysis

(See Appendix F for the scatter plots)

The parameters were evaluated in a correlation analysis. The SD value was analysed with respect to wind statistics. And the measured stress was analysed with respect to both wind statistics and temperature. An analysis of the relationship between the SD value and the temperature was found to be not relevant, due to an assumption that the temperature is not reflected in the SD value.

A correlation analysis would be of interest to get an insight into whether there might exist a relationship between the parameters.

Table 5 shows the different interpretations of the calculated value. The value is always between -1 and 1. A number very close to zero implies weak or no linear relationship between the two parameters evaluated. A higher number indicates a stronger relationship, with 1 giving a perfect linear relationship. A negative value implies a opposite linear relationship, e.g., when x increases, y decreases with a linear relationship. The correlation analysis cannot conclude with causation, meaning that even if a strong relationship is detected doesn't necessarily mean that the change in one parameter causes the change of the other. Hence, no deterministic conclusions can be drawn based on a correlation analysis.

Table 5: r-value interpretation

r	Strength	Direction
$r>0.5$	Strong	Positive
$0.3<r<0.5$	Moderate	Positive
$0<r<0.3$	Weak	Positive
0	None	None
$-0.3<r<0$	Weak	Negative
$-0.5<r<-0.3$	Moderate	Negative
$-0.5>r$	Strong	Negative

Table 6 shows the calculated r-values for the month November in 2020, for sensor position PW S00kl12 and PW S05kl12. The relationship between SD and mean wind for both S00 and S05 is calculated to have a moderate relationship. Both mean wind and temperature is found to have a weak relationship with the measured stress in sensor position S00. However, for S05 a strong relationship was indicated between the measured stress and the mean wind, and no relationship between the measured stress and the temperature.

The r-values for the two SD analysis can seem reasonable as the mean wind speed for November, as seen in Figure 37, in was relatively high some days, meaning the bridge probably experienced swaying. In addition, the temperature was low and judging by the r-values seem to have little or no impact on the measurements.

Table 6: r-values for November 2020

November 2020		
PWS00kl12		
Parameters	Mean Wind	Temperature
SD	0,47	-
Measured Stress	-0,28	-0,24
PWS05kl12		
Parameters	Mean Wind	Temperature
SD	0,43	-
Measured Stress	0,52	-0,02

Though, the correlation between measured stress and the mean wind for S00 came out to a weak negative relation and the same variables for S05 came out to a strong positive. It is not straightforward to find a reason for this discrepancy.

Table 7: r-values for June 2021

June 2021		
PWS00kl12		
Parameter	Mean Wind	Temperature
SD	0,14	-
Measured Stress	-0,15	0,37
PWS05kl12		
Parameter	Mean Wind	Temperature
SD	0,13	-
Measured Stress	-0,15	0,51

Table 7 lists the calculated r-values for the correlation analysis for the month of June 2021. All the different r-values seem to point in the direction of an assumption that the wind has little or no effect on the measured stress for this month. Concurrently, the r-values for the temperature implies moderate or strong linear relationship with the measured stress.

7.5 Discussion

The analysis gave a broad variety of r-values between the different parameters. One thing that could cause the discrepancies is the difference in temperature level between the two months assessed. In the warmer summer months, the temperature seems to impact the sensors to some degree. Accordingly, in the winter months the temperature seems to have a lower correlation with the stress measurements. With regards to the sensors being sensitive to temperature, this makes sense.

These analyses were performed on a data sample within a limited time frame. A similar analysis but with broader data sample, e.g., a whole year, could be interesting. In this way the varying temperature throughout the year would be taken into consideration.

However, the main thing to take from this analysis is that there are uncertainties, in the measurements and in the interpretation of them.

Chapter 8

Concluding remarks

The Digital Twin concept as it is defined, has a great deal to offer the construction industry. However, the research can be defined to still be in the early ages and challenges with uncertainties, automated model updating and lack of standardisation slowing the process. Nevertheless, the eagerness within the research effort of realising this concept appears to be strong.

The evaluated sensor layout in this thesis could be used to create a digital twin for the support structure. To create a digital twin for the whole bridge would need additional sensors mounted on the concrete structure. The support structure is one system, the bridge is another, even though they are firmly connected. There are uncertainties will all digital twin systems. If the objective of the sought solution is to generate information and analysis of the bridge, it is unfortunate to have all sensors mounted on the support structure and none on the actual concrete structure as the interconnection between them adds another dimension of uncertainty.

The ultimate vision for a digital twin as described in many of the definitions is that not only can it report a damage, but the damage can be located, the seriousness of it can be evaluated and it can provide an estimation of remaining service life amongst other things. The sensors on the support structure are unable to contribute with data that can achieve discoveries with this level of precision. However, a digital twin of the support structure could be used for monitoring changes of load distribution on the bridge. A distinct change in measured stresses by the sensors on the support structure could indicate a significant event that may have caused damage to the bridge, and a visual inspection could be initiated based on this data. This needs to be researched further.

The 3D modelling based of the scanned point cloud and the analysis did not turn out as planned in this thesis and that was not due to lack of attempts. However, there is also value in sharing what went wrong.

Further work

Next steps in process of creating the digital twin:

- Make a very simplified model of one of the arch sections, suggest the arch section at the hinge as their interface between the arches, the frames and the bridge is perhaps the least challenging to define there.
- Make a 3D scan of the concrete structure, recommended to use a UAV or a mobile scanner for this procedure as the bridge is so narrow making it impossible to scan from the bridge deck without being a hindrance for the traffic.
- Evaluate the possibility of monitoring the deflection of the levelling bolts using a mounted camera.
- Correlation analysis of the relationship between the parameters in chapter 7 over a longer period, maybe a whole year. And perhaps with other parameters as wind seemed to have little effect.
- Have a truck with a known load drive over the bridge and evaluate the response in the sensor output.

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Appendix A

Bridge statistics

Number of bridges

	Culvert bridge	Pedestrian bridge	Road bridge
County municipality	2 947	514	8 215
Nye Veier AS	48	1	74
Norwegian Public Roads Administration	2 186	452	2 930
Total	5 181	967	11 219

Average length pr owner

	Average length [km]
County municipality	22,9
Nye Veier AS	47,6
Norwegian Public Roads Administration	38,1
Total	27,9

Number/area of bridges distributed by length

Length	Number of bridges	Sum length [m]	Sum area [m^2]
<10 m	9 486	48 963	568 934
10-49,9 m	5 674	125 660	1 052 593
50-99,9 m	1 239	83 299	771 835
>=100 m	925	226 209	2 339 707
Length not registred	43	0	0
Total	17 367	484 131	4 733 069

Number/area of bridges distributed by year of construction

Year of construction	Number	Sum area [m²]	Percent [%]
<1920	195	19 700	1,12
1920-29	194	29 834	1,12
1930-39	679	69 693	3,91
1940-49	719	70 770	4,14
1950-59	1 888	281 329	10,87
1960-69	2 843	521 037	16,37
1970-79	3 218	879 784	18,53
1980-89	2 643	629 430	15,22
1990-99	2 031	755 877	11,69
2000-09	1 325	640 643	7,63
>2010-	1 496	825 466	8,61
Year of construction not registered	136	9 505	0,78
Total	17 367	4 733 069	100

Average age of bridges distributed by owner

	Average construction year		Average age [y]
County municipality	1972		50
Nye Veier AS	2017		5
Norwegian Public Roads Administration	1985		37
Average year of construction	1976		46

Appendix B

Dead weight calculations

Egenvekt betongbro	17485,85705	kN	
Egenvekt extra layer	2079	kN	Source: Teigen
Rekkverk	99	kN	Source: Hangaard
Egenvekt rørbuer	1414,963967	kN	See calculations below
Egenvekt rammer	161,2566299	kN	See calculations below
Jekkebjelker	202,8476133	kN	See calculations below
Sum	**21442,93**	**kN**	
			i kg 2186569,85

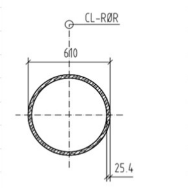
Length bridge:	198	m
weight extra laye	10,50	kN/m
weight rails:	0,5	kN/m
g=	9,80665	m/s^2
Unit weight:	**108,30**	**kN/m**

Frames	Weight pr frame [kg]	# frames	Sum [kg]	[N]	[kN]	
Frame type 1	827,7	2	1655,4	16233,928	16,2339284	
Frame type 2	781,7	6	4690,2	45995,15	45,9951498	
Frame type 3	870,2	8	6961,6	68269,975	68,2699746	
Frame type 4	784,1	4	3136,4	30757,577	30,7575771	
Sum					**161,25663**	**kN**
Source: Samlefil SB-tegninger (2D-drawings)						

Jacking console	vekt [kg]	N	kN	
Materialer	17736,7	173937,61	173,93761	
Jekk	2948	28910,004	28,910004	
Sum			**202,84761**	**kN**
Source: Samlefil SB-tegninger				

Arches

Arch part	#	Length [mm]	Total [mm]	[m]	
end-piece South	2	4424,6	8849,2	8,8492	
10m towards end soı	2	10010,4	20020,8	20,0208	
ordinary 10m	14	10010,4	140145,6	140,1456	
10m towards middle	2	10010,4	20020,8	20,0208	
middle	2	5005,2	10010,4	10,0104	
10 towards middel	2	10010,4	20020,8	20,0208	
ordinary 10m	14	10010,4	140145,6	140,1456	
10m towards end no	2	10010,4	20020,8	20,0208	
end-piece north	2	5194,4	10388,8	10,3888	
Sum:				389,6228	m
			Source: Samlefil SB-tegninger		



A=π*r^2

r_o=	305	mm
A_o=	292246,6566	mm^2
r_i	279,6	mm
A_i=	245597,6499	mm^2
A_arch [mm^2]=	46649,00666	mm^2
A_arch [m^2]=	0,046649007	m^2

Kilde: Samlefil SB-tegninger

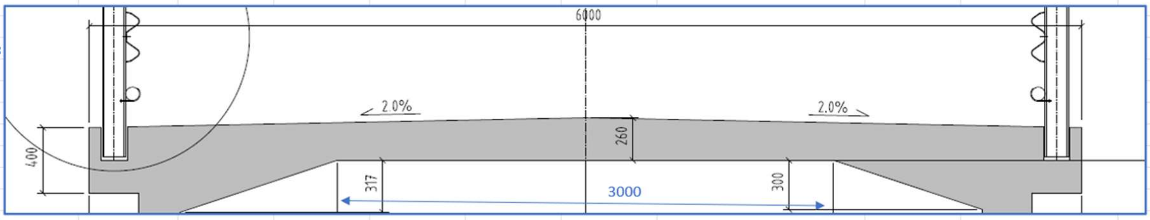
arch volume	L*A	
	18,17551659	m^3

Density steel	77,85	kN/m^3	
	77850	N/m^3	Source: NS-EN 1991-1-1:2002+NA:2019 Density for steel: 77,0 to 77,85 kN/m^3, chose highest value for safety

SUM Weight Arches	**1414963,967**	**N**
in kN:	**1414,964**	

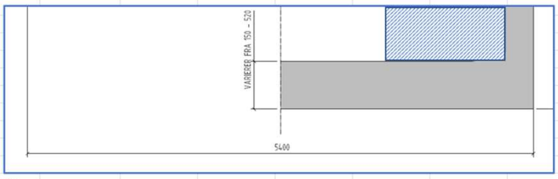
Assumptions and simplifications:
Disregard slope of deck
Assume 250mm thickness of girder on one side, and 300mm on the other
Disregard the haunches (no: vouter) in bottom slab
Disregard cutout for railing
Disregard the difference in haunches in the top of slab

"Top":



Whole				
Hight_whole=	260	+	317 =	577 mm
Width_whole=	6000	mm		
Area_whole=	3462000	mm2		
SideCut				
Hight_sidecut=	177	mm		
Width_sidecut=	300	mm	Area_top = Area_whole - Area_SideCut - Area_MiddleCut - Area_Haunch	
Area_sidecut=	53100	mm2	2103650 mm2	
*2	106200	mm2		
MiddleCut				
Hight_middlecut	317	mm		
Width_middlecut	3000	mm		
Areal_midtkutt	951000	mm2		
Haunch				
Hight_haunch	317	mm		
Length_haunch	950	mm		
*2	301150	mm2		

"Bottom":



Smallest area:		
Hight_min:	150	mm
Width:	5400	mm
Area_min_bottom	810000	mm2
Largest area:		
Hight_max:	520	mm
Width:	5400	mm
Area_max_bottom	2808000	mm2

"Walls": VARIERER FRA 2200 – 11290

Area wall 250mm min		
Hight min	2200	mm
Width	250	mm
Area wall 250mm min	550000	mm2
Area wall 250mm max		
Hight max	11290	mm
Width	250	mm
Area wall 250mm max	2822500	mm2
Area wall 300mm min		
Hight min	2200	mm
Width	300	mm
Area wall 300mm min	660000	mm2
Area wall 300mm max		
Hight max	11290	mm
Width	300	mm
Area wall 300mm max	3387000	mm2

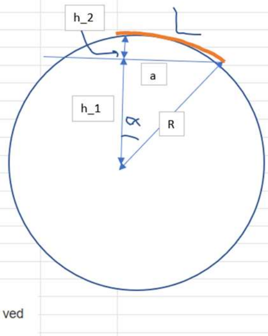
Chord lenght:

radius/hypotenuse		^2	
R=	493000 mm	2,43049E+11	
minor cathetus			
a=	99000 mm	9801000000	
major cathetus			
h_1=	$\sqrt{R^2 - a^2}$	482957,5551	mm
h_2	R-h_1	10042,44493	mm
angle			
2α=	$\tan^{-1}\frac{a}{h\_1}$	11,5844091	°

Er vinkelen målt i grader, så er lengden av en bue utspent av vinkelen v gitt ved

$$L = \pi r \frac{\alpha}{180}$$

L/2=	99677,73778 mm
L=	199355,4756 mm



L/2:	99677,73778	mm
	Number of steps:	
Defining number of steps:		50
(L/2)/50:	1993,554756	mm/step

Max hight-min hight sides		
	9090	
Increase in height pr ste	181,8	mm/step

Max hight-min hight bunn		
	370	
Increast in height pr ste	7,4	mm/step

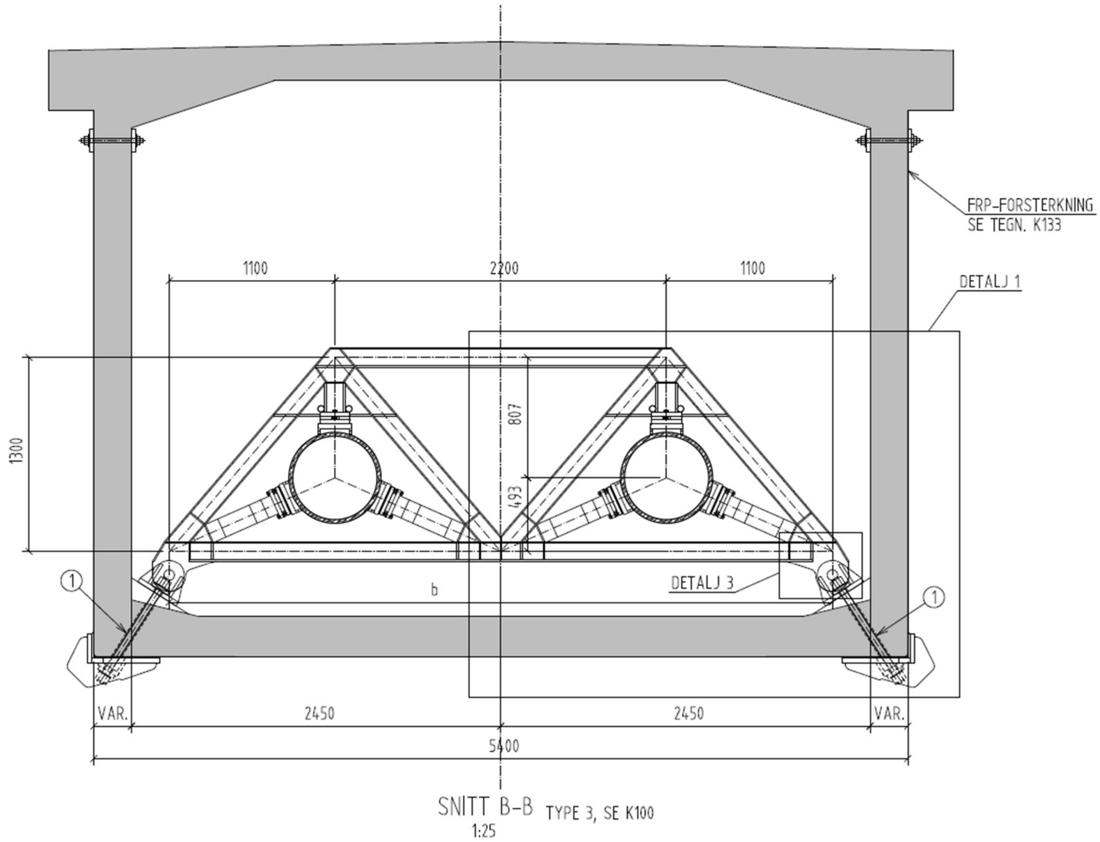
	[mm2]	[mm2]	[mm2]	[mm2]	[mm2]	[mm]	[mm3]	[m3]
Steg	Area top	Area bottom	Area side 250	Area side 300	Sum Areas	StepLength	Volume	
1	2103650	810000	550000	660000	4123650	1993,55476	8220722068	8,22072207
2	2103650	849960	595450	714540	4263600	1993,55476	8499720056	8,49972006
3	2103650	889920	640900	769080	4403550	1993,55476	8778718044	8,77871804
4	2103650	929880	686350	823620	4543500	1993,55476	9057716032	9,05771603
5	2103650	969840	731800	878160	4683450	1993,55476	9336714020	9,33671402
6	2103650	1009800	777250	932700	4823400	1993,55476	9615712008	9,61571201
7	2103650	1049760	822700	987240	4963350	1993,55476	9894709996	9,89471
8	2103650	1089720	868150	1041780	5103300	1993,55476	10173707984	10,173708
9	2103650	1129680	913600	1096320	5243250	1993,55476	10452705972	10,452706
10	2103650	1169640	959050	1150860	5383200	1993,55476	10731703961	10,731704
11	2103650	1209600	1004500	1205400	5523150	1993,55476	11010701949	11,0107019
12	2103650	1249560	1049950	1259940	5663100	1993,55476	11289699937	11,2896999
13	2103650	1289520	1095400	1314480	5803050	1993,55476	11568697925	11,5686979
14	2103650	1329480	1140850	1369020	5943000	1993,55476	11847695913	11,8476959
15	2103650	1369440	1186300	1423560	6082950	1993,55476	12126693901	12,1266939
16	2103650	1409400	1231750	1478100	6222900	1993,55476	12405691889	12,4056919
17	2103650	1449360	1277200	1532640	6362850	1993,55476	12684689877	12,6846899
18	2103650	1489320	1322650	1587180	6502800	1993,55476	12963687865	12,9636879
19	2103650	1529280	1368100	1641720	6642750	1993,55476	13242685853	13,2426859
20	2103650	1569240	1413550	1696260	6782700	1993,55476	13521683841	13,5216838
21	2103650	1609200	1459000	1750800	6922650	1993,55476	13800681829	13,8006818
22	2103650	1649160	1504450	1805340	7062600	1993,55476	14079679817	14,0796798
23	2103650	1689120	1549900	1859880	7202550	1993,55476	14358677805	14,3586778
24	2103650	1729080	1595350	1914420	7342500	1993,55476	14637675793	14,6376758
25	2103650	1769040	1640800	1968960	7482450	1993,55476	14916673781	14,9166738
26	2103650	1809000	1686250	2023500	7622400	1993,55476	15195671769	15,1956718
27	2103650	1848960	1731700	2078040	7762350	1993,55476	15474669757	15,4746698
28	2103650	1888920	1777150	2132580	7902300	1993,55476	15753667745	15,7536677
29	2103650	1928880	1822600	2187120	8042250	1993,55476	16032665733	16,0326657
30	2103650	1968840	1868050	2241660	8182200	1993,55476	16311663722	16,3116637
31	2103650	2008800	1913500	2296200	8322150	1993,55476	16590661710	16,5906617
32	2103650	2048760	1958950	2350740	8462100	1993,55476	16869659698	16,8696597
33	2103650	2088720	2004400	2405280	8602050	1993,55476	17148657686	17,1486577
34	2103650	2128680	2049850	2459820	8742000	1993,55476	17427655674	17,4276557
35	2103650	2168640	2095300	2514360	8881950	1993,55476	17706653662	17,7066537
36	2103650	2208600	2140750	2568900	9021900	1993,55476	17985651650	17,9856516
37	2103650	2248560	2186200	2623440	9161850	1993,55476	18264649638	18,2646496
38	2103650	2288520	2231650	2677980	9301800	1993,55476	18543647626	18,5436476
39	2103650	2328480	2277100	2732520	9441750	1993,55476	18822645614	18,8226456
40	2103650	2368440	2322550	2787060	9581700	1993,55476	19101643602	19,1016436
41	2103650	2408400	2368000	2841600	9721650	1993,55476	19380641590	19,3806416
42	2103650	2448360	2413450	2896140	9861600	1993,55476	19659639578	19,6596396
43	2103650	2488320	2458900	2950680	10001550	1993,55476	19938637566	19,9386376
44	2103650	2528280	2504350	3005220	10141500	1993,55476	20217635554	20,2176356
45	2103650	2568240	2549800	3059760	10281450	1993,55476	20496633542	20,4966335
46	2103650	2608200	2595250	3114300	10421400	1993,55476	20775631530	20,7756315
47	2103650	2648160	2640700	3168840	10561350	1993,55476	21054629518	21,0546295
48	2103650	2688120	2686150	3223380	10701300	1993,55476	21333627506	21,3336275
49	2103650	2728080	2731600	3277920	10841250	1993,55476	21612625495	21,6126255
50	2103650	2768040	2777050	3332460	10981200	1993,55476	21891623483	21,8916235
51	2103650	2808000	2822500	3387000	11121150	1993,55476	22170621471	22,1706215
							774979260236,15	774,97926

CUT OUT FROM BOTTOM SLAB AT HINGE						Volume concrete	774979260,2	cm3
	L=	21000	mm			density concrete	2,3	g/cm3
	W=	4000	mm	*simplification				
	H=	150	mm			Weight:	1782452299	g
A=	L*W=	84000000	mm2				1782452,299	kg
V=	A*H=	1,26E+10	mm3				1782,452299	tonn
	mm3 to cm3=	12600000	cm3			Force:	17485857,05	N
	g	28980000	g				17,48585705	MN
	kg	28980	kg			*2=	34,9717141	MN
	to N	284293,8	N					
	to kN	284,2938	kN		Volume concrete - Cut outs=			
	to MN	0,2842938	MN			**TOTALT:**	**34,4031265**	**MN**
Two Cuts	*2	0,5685876	MN					

Mechanical Pressure by dead load						
Bridge slab Length:	99000	mm				
Bridge Slab Width:	6000	mm				
Area:	**1188000000**	**mm2**	(both arms)	1188	**m2**	
Dead weigh without support systemt:	**1616,4**	**tonne**				
Dead weight in kg	1616400	kg				
gravity:	9,80665	m/s2				
	9806,65	**mm/s2**				
Force:	15851469060	kg*mm/s2				
	15851469,06	kg*m/s2				
						1Pa=1N/1m2
Pressure=F/A	0,013342987	N/mm2	MPa	(kg*m/s2)/mm2	kg/m*s2	1MPa=1N/mm2
	0,001334299	0.1MPa				
Total weight with support system						
in kg:	2020472,66	kg	**2020,47266**	**tonne**		
Force	19814068,21	kg*m/s2	19814068,21			
Pressure=	0,016678509	N/mm2	Mpa			
DeadLoad	**0,016678509**	**MPa**				
				1,700734562	tonne/m2	
	Abaqus units			0,016678509	Mpa	
	Mass	tonne				
	Length	mm				
	Time	s				
	Temp	K				
	Velocity	mm/s				
	Acceleration	mm/s2				
	Force	N				
	Moment	Nmm				
	Pressure	Mpa				
	Density	tonne/mm3				

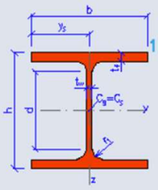
Appendix C

Frame geometry



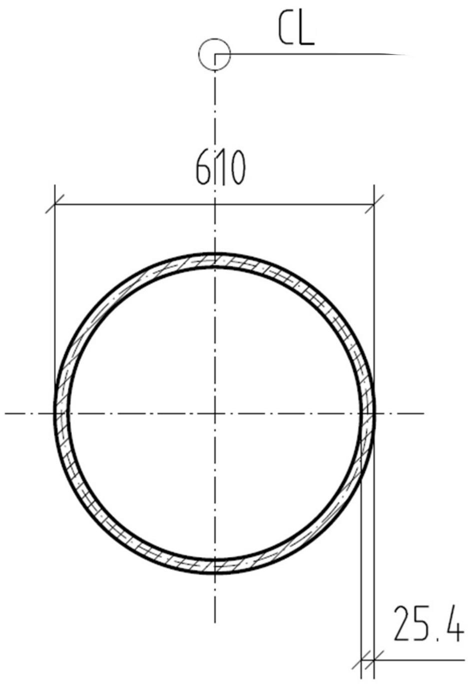
Frame	L [mm]	A [mm^2]	I_S [10^6 mm^4]	I_L [10^5 mm^4]
1	1210	729,8	528,5	152,0
2	1149	620,2	300,5	129,2
3	1080	627,7	266,1	130,8
4	1019	604,9	241,2	126,0
5	940	580,8	217,7	121,0
6	844	566,9	165,8	118,1
7	791	541,3	176,6	112,8
8	727	497,5	137,1	103,6
9	712	487,2	128,8	101,5
10	661	452,3	103,1	94,2

Cross-section of the frames in the truss

HE140A			
Geometry		Section properties	
h = 133 mm		Axis y	Axis z
b = 140 mm		I_y = 1.03E+7 mm^4	I_z = 3.89E+6 mm^4
t_f = 8.5 mm		W_{y1} = 1.55E+5 mm^3	W_{z1} = 5.56E+4 mm^3
t_w = 5.5 mm		$W_{y,pl}$ = 1.74E+5 mm^3	$W_{z,pl}$ = 8.48E+4 mm^3
r_1 = 12 mm		i_y = 57.30 mm	i_z = 35.20 mm
y_s = 70 mm		S_y = 8.68E+4 mm^3	S_z = 4.24E+4 mm^3
d = 92 mm		Warping and buckling	
A = 3142 mm^2		I_w = 1.51E+10 mm^6	I_t = 8.13E+4 mm^4
A_L = 0.79 $m^2.m^{-1}$	G = 24.7 $kg.m^{-1}$	i_w = 32.54 mm	i_{pc} = 67.28 mm

Simplifications for frames: All frames modelled after frame type 3, which is the most used throughout the bridge, in addition all beam profiles are specified as HE140A as this is the profile most used in the frame structure.

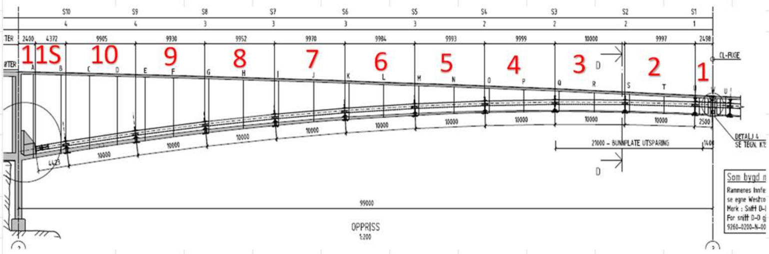
The cross-section of the arches



Appendix D

Thickness of bottom slab shells calculation

South



Comment

Making shell parts between all frame positions to simplify the process of adding the frames

To account for the varying thickness of the slab througout the cantliever arm

Assumption: linear increase of thickness

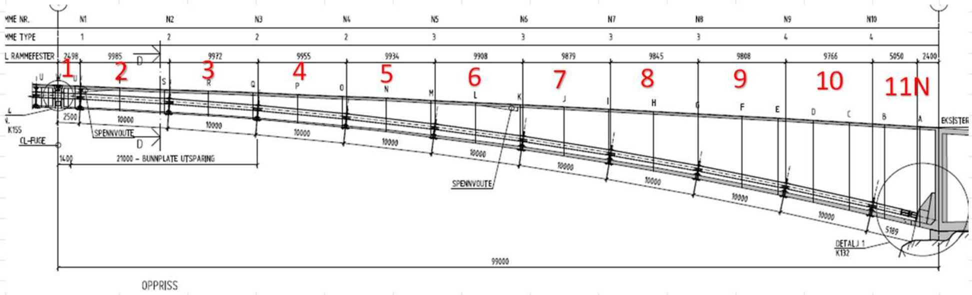
Thickness		
Max:	520	mm
Min:	150	mm
Steps:	10	
+t for each step:	37	mm

STEP	t	
1	150	mm
2	187	mm
3	224	mm
4	261	mm
5	298	mm
6	335	mm
7	372	mm
8	409	mm
9	446	mm
10	483	mm
11	520	mm

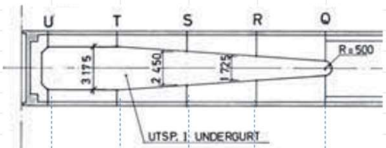
South Cantilever Arm			
PART	length	width	thickness
1	2500	6000	150
2	10000	6000	187
3	10000	6000	224
4	10000	6000	261
5	10000	6000	298
6	10000	6000	335
7	10000	6000	372
8	10000	6000	409
9	10000	6000	446
10	10000	6000	483
11S	6823	6000	520

North Cantilever Arm			
PART	length	width	thickness
1	2500	6000	150
2	10000	6000	187
3	10000	6000	224
4	10000	6000	261
5	10000	6000	298
6	10000	6000	335
7	10000	6000	372
8	10000	6000	409
9	10000	6000	446
10	10000	6000	483
11N	7589	6000	520

These are subjeccted to cut out - so they will be modeled as one part as a simplification



Cutout



5000 5000 5000 5000 mm

GEOMETRI FRITT FREMBYGG				
SNITT	OK KT m	X m	H mm	Hu mm
Q	18.506	21.90	2 645	150
R	18.725	16.90	2 465	150
S	18.940	11.90	2 331	150
T	19.149	6.90	2 244	150
U	19.354	1.90	2 203	150
℄ FELT	19.430	0	2 200	150

Part 123	length	width	thickness
	22500	6000	187

Parts to make - summary			
PART	length	width	thickness
123*	22500	6000	187
4	10000	6000	261
5	10000	6000	298
6	10000	6000	335
7	10000	6000	372
8	10000	6000	409
9	10000	6000	446
10	10000	6000	483
11S	6823	6000	520
11N	7589	6000	520

* w/cutout

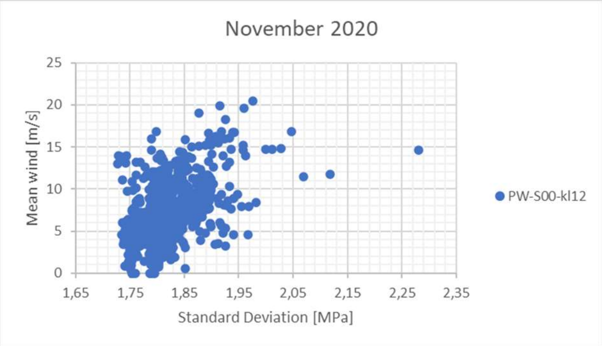
Appendix E

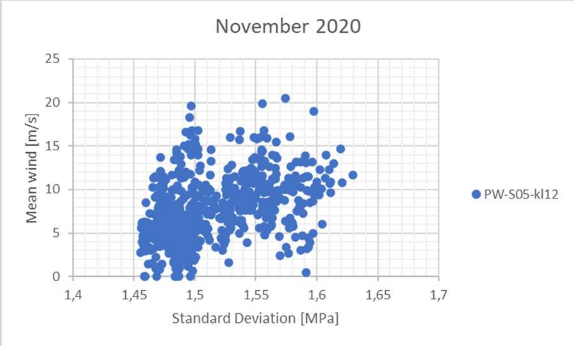
Levelling measurements calculations

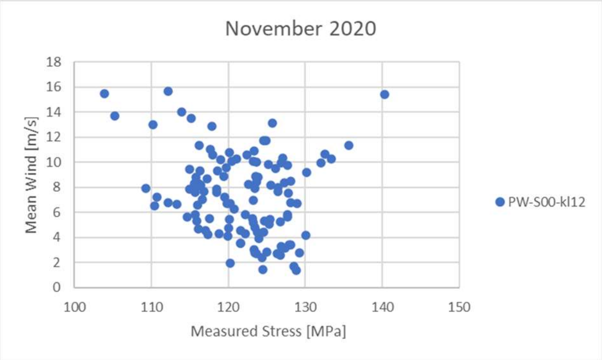
Leveling measurements	Approximate location in x-direction [m] a relative to the structures own coordinate system having origo defined in the hinge											
					Date: 12.01.2018	Date: 09.11.2018	Date: 26.11.2018	Date: 18.12.2019				
Bolt	x	Change in distance	x corr	x wrt origo	y-value (hight) start of project	y-value (hight) before jacking (steel structure mounted)	y-value (height) after jacking (before asphalt)	y- value after jacking and after asphalt)	Change in height from January-18 to November -18	Change in height after jacking	Change in height after added asphalt layer	
NB7	306146,264	0	0	-94,293791	22,493	22,489	22,491	22,492	-0,004	0,002	0,003	
NB9	306149,875	3,611	3,891442	-94,293791	22,412	22,407	22,410	22,41	-0,005	0,003	0,003	
NB11	306153,575	3,7	3,987354	-90,402349	22,280	22,274		22,277	-0,006			
NB13	306157,164	3,589	3,867734	-86,414995	22,177	22,170	22,179	22,178	-0,007	0,009	0,008	
NB13B	306160,934	3,77	4,062791	-82,547261	22,051	22,042	22,054	22,053	-0,009	0,012	0,011	
NB15	306164,605	3,671	3,956102	-78,48447	21,928	21,916	21,932	21,929	-0,012	0,016	0,013	
NB17	306168,85	4,245	4,574681	-74,528368	21,774	21,761		21,777	-0,013			
NB19	306173,68	4,83	5,205114	-69,953688	21,605	21,588		21,612	-0,017			
NB21	306178,056	4,376	4,715855	-64,748574	21,461	21,437		21,47	-0,024			
NB23	306182,927	4,871	5,249298	-60,032719	21,315	21,286	21,342	21,325	-0,029	0,056	0,039	
NB25	306187,118	4,191	4,516487	-54,783421	21,158	21,123		21,174	-0,035			
NB27	306192,147	5,029	5,419569	-50,266935	21,001	20,958	21,044	21,02	-0,043	0,086	0,062	
NB29	306196,218	4,071	4,387167	-44,847366	20,829	20,778	20,884	20,853	-0,051	0,106	0,075	
NB31	306200,986	4,768	5,138299	-40,460199	20,667	20,605	20,735	20,698	-0,062	0,130	0,093	
NB33	306205,226	4,24	4,569292	-35,3219	20,491	20,420	20,575	20,53	-0,071	0,155	0,110	
NB35	306210,035	4,809	5,182483	-30,752607	20,290	20,205	20,392	20,345	-0,085	0,187	0,140	
NB37	306214,222	4,187	4,512176	-25,570125	20,131	20,034		20,194	-0,097			
NB39	306219,029	4,807	5,180327	-21,057948	19,904	19,794	20,034	19,982	-0,110	0,240	0,188	
NB41	306223,372	4,343	4,680292	-15,877621	19,714	19,590	19,860	19,803	-0,124	0,270	0,213	
NB43	306228,233	4,861	5,238521	-11,197329	19,453	19,309	19,620	19,556	-0,144	0,311	0,247	
NB45	306233,113	4,88	5,258997	-5,9588079	19,205	19,039	19,391	19,324	-0,166	0,352	0,285	
NB47	306236,302	3,189	3,329309	5,9588079	19,067	18,900	19,251	19,186	-0,167	0,351	0,286	
NB49	306240,346	4,044	4,221928	10,180736	18,903	18,756	19,067	19,011	-0,147	0,311	0,255	
NB51	306245,229	4,883	5,097842	15,278578	18,701	18,569	18,844	18,795	-0,132	0,275	0,226	
NB53	306250,27	5,041	5,262794	20,541371	18,525	18,409	18,664	18,607	-0,116	0,255	0,198	
NB55	306254,282	4,012	4,18852	24,729891	18,374	18,271	18,497	18,447	-0,103	0,226	0,176	
NB57	306258,376	4,094	4,274128	29,004019	18,169	18,077	18,275	18,231	-0,092	0,198	0,154	
NB59	306263,469	5,093	5,317082	34,3211	17,941	17,862	18,028	17,992	-0,079	0,166	0,130	
NB61	306268,297	4,828	5,040422	39,361522	17,715	17,650	17,788	17,758	-0,065	0,138	0,108	
NB63	306272,65	4,353	4,544523	43,906045	17,502	17,446	17,562	17,537	-0,056	0,116	0,091	
NB65	306277,417	4,767	4,976738	48,882783	17,257	17,211	17,306	17,285	-0,046	0,095	0,074	
NB67	306281,754	4,337	4,527819	53,410602	17,028	16,990	17,067	17,051	-0,038	0,077	0,061	
NB69	306286,231	4,477	4,673979	58,084581	16,774	16,744	16,805	16,792	-0,030	0,061	0,048	
NB71	306290,763	4,532	4,731399	62,81598	16,519	16,494	16,542	16,531	-0,025	0,048	0,037	
NB73	306295,366	4,603	4,805523	67,621502	16,265	16,245	16,282	16,274	-0,020	0,037	0,029	
NB75	306299,935	4,569	4,770027	72,391529	15,993	15,978	16,005	16	-0,015	0,027	0,022	
NB77	306304,665	4,73	4,93811	77,329639	15,716	15,705	15,724	15,72	-0,011	0,019	0,015	
NB79	306308,14	3,475	3,627893	80,957532	15,499	15,490	15,504	15,501	-0,009	0,014	0,011	
NB81	306311,758	3,618	3,777185	84,734717	15,269	15,263	15,273	15,271	-0,006	0,010	0,008	
NB83	306315,321	3,563	3,719765	88,454481	15,042	15,037	15,043	15,043	-0,005	0,006	0,006	
NB85	306319,127	3,806	3,973456	92,427938	14,794	14,791	14,794	14,794	-0,003	0,003	0,003	
NB87	306322,721	3,594	3,752129	96,180066	14,572	14,570	14,572	14,572	-0,002	0,002	0,002	

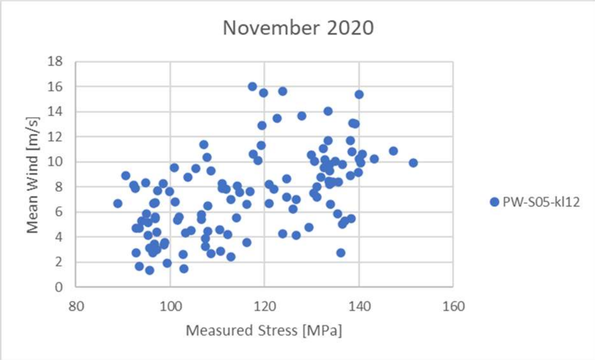
Appendix F

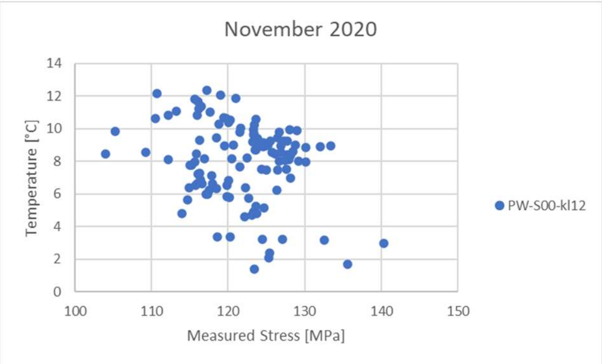
Correlation Scatter Plots

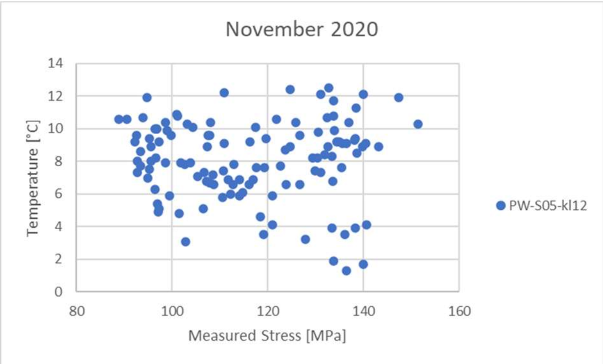


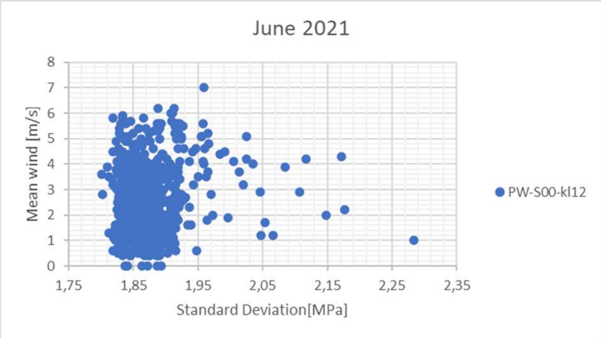


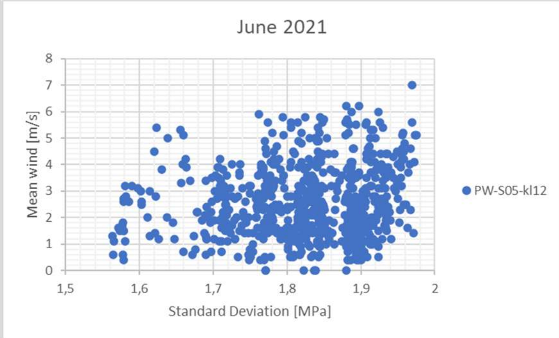


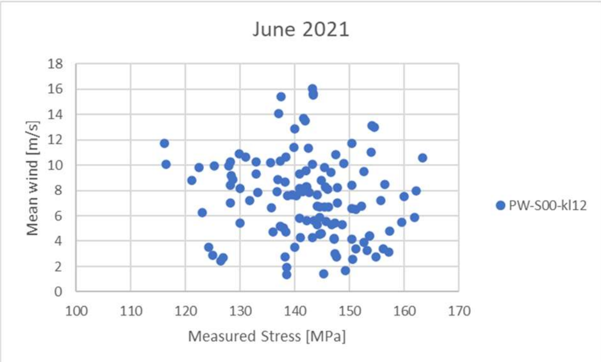


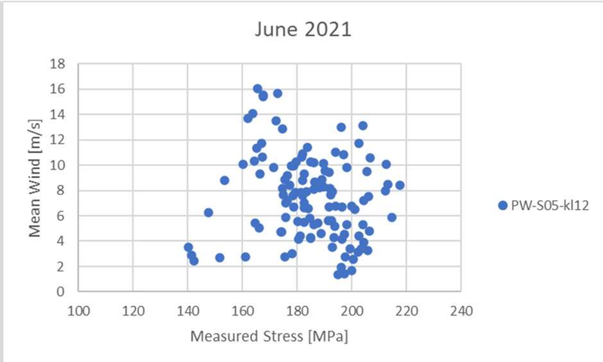


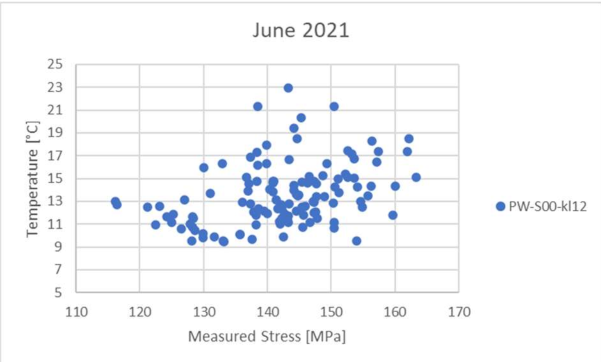


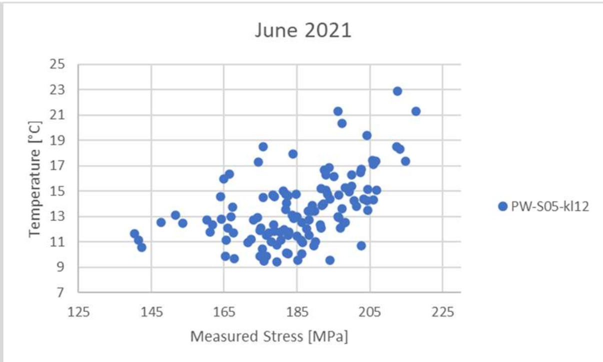

June 2021
Mean wind [m/s]
Standard Deviation[MPa]
PW-S00-kl12


June 2021
Mean wind [m/s]
Standard Deviation [MPa]
PW-S05-kl12


June 2021
Mean wind [m/s]
Measured Stress [MPa]
PW-S00-kl12


June 2021
Mean Wind [m/s]
Measured Stress [MPa]
PW-S05-kl12


June 2021
Temperature [°C]
Measured Stress [MPa]
PW-S00-kl12


June 2021
Temperature [°C]
Measured Stress [MPa]
PW-S05-kl12