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STUDY OF FAILURE PROFILES IN THE BRIDGE STRUCTURES

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Abstract (max 150 words):

Bridge safety is an indispensable part of transportation safety. However, each bridge is unique with respect to its material, design and the environment which it is located in, and other relevant factors. This makes defining a unified framework for studying and categorizing failures in the bridges a difficult task. The current report aims at taking the first step to reach such a goal.

This report addresses the issue of the bridge failure. First, it introduces different bridge characteristics. The emphasis is on introducing different types of bridges including differences in the design, material, structure forms, load type, condition and environment.

In the second part, the report focuses on failure profile for the bridge structures. This includes discussing different failure causes, failure mechanism, and their corresponding modes and types.

Finally, the findings from the first two parts are applied in a sample case study. The data is from BRUTUS, the database of Norwegian Public Roads Administration (SVV). This data includes the information of the 152 bridge structures located in Trondheim municipality. The data provides information on the bridge characteristics e.g. material type, bridge design, application and age. The bridges in Trondheim are categorized based on the characteristics and their failure status are investigated based on the risk matrices.

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TERMINOLOGY

TERMS	DEFINITIONS
Collapse	"*Development of failure mechanisms in a structure to a degree involving disintegration and falling (parts of) structural members*" (ES ISO 2394, 2012).
Condition Attributes	"*Characteristics that relate to the current condition of a bridge or bridge element. These may include element ratings, component ratings, and specific damage modes or mechanisms that have a significant effect on the reliability of an element"* (NCHRP, 2014).
Condition/ durability limit state	*"Well-defined and controllable limit state without direct negative consequences, which is often an approximation to a real limit state that cannot be well defined or is difficult to calculate"* (ES ISO 2394, 2012).
Damage	"*Unfavorable change in the condition of a structure that can affect the structural performance unfavorably*" (ES ISO 2394, 2012).
Design Attributes	"*Characteristics of bridge or bridge element that are part of the element's design. These attributes typically do not change over time except when renovation, rehabilitation, or preservation activities"* (NCHRP, 2014).
Design criteria	*"Quantitative formulations describing the conditions to be fulfilled for each limit state"* (ES ISO 2394, 2012).
Environmental influences	"*Physical, chemical, or biological influences which may deteriorate the materials constituting a structure, which in turn may affect its serviceability and safety in an unfavorable way"* (ES ISO 2394, 2012).
Irreversible limit states	"*Limit states which will remain permanently exceeded when the actions which caused the exceedance are no longer present"* (ES ISO 2394, 2012).
Life cycle	"*Life cycle incorporates initiation, project definition, design, construction, commissioning, operation, maintenance, refurbishment, replacement, deconstruction, and ultimate disposal, recycling, or re-use of the structure (or parts thereof), including its components, systems, and building services*" (ES ISO 2394, 2012).
Limit states	"*State beyond which a structure no longer satisfies the design criteria"* (ES ISO 2394, 2012).
Load	"*Weight distribution throughout a structure"* (Williams, 2009).

TERMS	**DEFINITIONS**
Loading Attributes	"*Loading characteristics that affect the reliability of a bridge or bridge element, such as traffic or environment"* (NCHRP, 2014).
Maintenance	**"***Activities and operations undertaken to manage and maintain an asset, e.g. inspection, assessment, renewal, upgrade, etc*." (TfL, 2011).
Performance indicator	**"***Parameter describing certain characteristic of the structural behavior*" (ES ISO 2394, 2012).
Probability of failure (PoF)	"*Factor describing the likelihood that an element will fail during a specified time period*" (NCHRP, 2014) (DNV-RP-G101, 2010).
Reversible limit states	"*Limit states which will not be exceeded when the actions which caused the exceedance are no longer present"* (ES ISO 2394, 2012).
Risk	"*Combination of the probability of an event and its consequence*" (NCHRP, 2014). (TfL, 2011) (BD 54/15, Management of post-tensioned CONCRETE BRIDGES, 2015).
Serviceability	**"***Ability of a structure or structural member to perform adequately for a normal use under all expected actions*" (ES ISO 2394, 2012).
Serviceability limit states	*"Limit state concerning the criteria governing the functionalities related to normal use"* (ES ISO 2394, 2012).
Structure	**"***Organized combination of connected parts including geotechnical structures designed to provide resistance and rigidity against various actions"* (ES ISO 2394, 2012).
Structural element	**"***Physically distinguishable part of a structure, e.g. column, beam, plate, foundation*" (ES ISO 2394, 2012).
Structural performance	**"***Qualitative or quantitative representation of the behavior of a structure (e.g. load bearing capacity, stiffness, etc.) related to its safety and serviceability, durability, and robustness*" (ES ISO 2394, 2012).
Structural safety	Structural safety is defined as a "*situation when structure demand is always less than the structure capacity*" (Rausand & Høyland, 2004).
Structural system	**"***Load/bearing members of a building or civil engineering structure and the way in which these members function together and interact with the environment*" (ES ISO 2394, 2012).
Ultimate limit states	*"Limit states concerning the maximum load-bearing capacity"* (ES ISO 2394, 2012).

ABBREVIATIONS

ABBREVIATIONS	DEFINITIONS
BRUTUS	Bridge management and preparedness (Bruforvaltning og –beredskap)
DNV	DET NORSKE VERITAS
FMEA	Failure Mode and Effects Analysis
N/D	Not Defined
NORSOK	Norsk Sokkels Konkurranseposisjon (The Norwegian Shelf's Competitive Position/ Norwegian Technology Standards Institution)
PoF	Probability of failure
SVV	Norwegian Public Roads Administration (Statens vegvesen)
TRD	Trondheim
UiT	University of Tromsø – Norges arktiske universitet

SUMMARY

Bridge safety is an indispensable part of transportation safety. However, each bridge is unique with respect to its material, design and the environment which it is located in, and other relevant factors. This makes defining a unified framework for studying and categorizing failures in the bridges a difficult task. The current report aims at taking the first step to reach such a goal.

This report addresses the issue of the bridge failure. First, it introduces different bridge characteristics. The emphasis is on introducing different types of bridges including differences in the design, material, structure forms, load type, condition and environment.

In the second part, the report focuses on failure profile for the bridge structures. This includes discussing different failure causes, failure mechanism, and their corresponding modes and types.

Finally, the findings from the first two parts are applied in a sample case study. The data is from BRUTUS, the database of Norwegian Public Roads Administration (SVV). This data includes the information of the 152 bridge structures located in Trondheim municipality. The data provides information on the bridge characteristics e.g. material type, bridge design, application and age. The bridges in Trondheim are categorized based on the characteristics and their failure status are investigated based on the risk matrices.

Key Words: Civil infrastructure, Bridge structures, Failure profile, Reliability

PREFACE

This thesis is written towards the fulfillment of the two-year master program in Technology and Safety in the High North at University of Tromsø (UiT), at Department of Technology and Safety. The course name is “TEK-3901 - Master thesis in engineering”. The project has been discussed and decided in cooperation with the supervisor, Maneesh Singh and it was initiated after an article in VG newspaper regarding the bridge status in Norway (VG, 2017). The article was published in 2017 and it attracted the interests of researchers and experts to discuss and investigate more regarding the failure profiles, maintenance, inspection, operations and the preventive measures for the bridges to be able to assure safer and more reliable structures and therefore transportations.

The primary concept of this report is regarding the failure profile in bridge structures. The specific case study is provided for a better understanding of the report concepts. The case study is about the presentation of the bridge status in Trondheim municipality based on BRUTUS database and interviews with Norwegian Public Roads administration (SVV) and further discussions regarding the results from different perspectives. Furthermore, the bridges with poor and very poor status are discussed elaborately.

The main objective of this project is to provide detailed information regarding the bridge types, bridge elements and how the failure profile can be explained in bridge structures. It can be expected that the reader will have a clear picture of detailed bridge structures and how its failure profiles can be defined.

The report involves of 4 main parts. The 1st part contains basic information about the project concepts and approaches. In the 2nd part, literature studies are explained including relevant terms and definitions. The 3rd part of the report is based on the concepts that are used for the case study. Finally, in the 4th part, conclusion and possible further studious are presented.

ACKNOWLEDGEMENT

Hereby, I would like to use this chance to show my appreciation to my dear supervisor "Maneesh Singh" for his sincere and continuous supports and inspirations which not only smoothed this project work, but also taught me valuable lessons regarding different issues which I can use in other phases of my life.

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Razieh Amiri

PART 1 – INTRODUCTION AND REVIEW

CHAPTER 1 – INTRODUCTION

1 INTRODUCTION

This chapter consists of background information, scope, motivations, objective and limitations. It also includes how the report has been structured to achieve the mentioned goals. Furthermore, it includes some research questions which are answered in chapter 6, “Conclusion and Further Studies”.

This thesis was initiated after an article in VG newspaper regarding the bridge status in Norway (VG, 2017). The article was published in 2017 and it attracted the interests of researchers and experts to discuss and investigate more regarding the failure profiles, maintenance, inspection, operations and the preventive measures for the bridges to be able to assure safer and more reliable bridge structures and therefore transportations. To do so, historical bridge data and complementary information from Norwegian Public Roads Administration (SVV) through interviews, “BRUTUS” database and reports are used in this project.

1.1 BACKGROUND

Civil structures play an important role in our daily life transportations. As one of the most important civil structures, bridges have been built because of fulfilling the constant human needs for communication, trading and transportations (Blockley, 2010). Engineers have used different materials, designs, architectures and other different elements in the bridge structures which provide more complexity to the bridge structures (Troyano, 2003).

Bridge safety is an indispensable part of transportation safety. In order to have reliable and safe structures, it is important to have a clear understanding of their system to be able to develop efficient and cost-efficient operation, maintenance and inspection plans (Miyamoto, Kawamura, & Nakamura, 2000). Each bridge is unique with respect to its material composition, design and the environment in which it is located and other applicable factors. This makes defining a unified framework for studying the failure profiles in the bridges a difficult task.

The current report aims at taking the first step to reach such a goal. The focus of this report is to present and approach the relevant issues based on an analysis for the bridges in Trondheim municipality.

The intention of this report is to provide a clear and structured picture of these issues and how they can be studied further. Therefore, it can enable engineers to understand the current issues in the bridge structures at the moment and to develop efficient and cost-efficient operation, maintenance and inspection plans.

1.2 AIM AND OBJECTIVE OF THE PROJECT

The main aim of this project is to develop the failure profile in the bridge structures which can assimilate the development of efficient and cost-efficient operation, maintenance and inspection plans.

The report introduces information regarding the bridge characteristics, reliability and the failure profile. Furthermore, the bridge status in Trondheim municipality has been presented based on the data from Norwegian Public Roads administration (SVV). The identified bridges with poor and very poor status are discussed in more detail.

1.3 RESEARCH QUESTIONS

Research questions are listed as below:

1. How bridge structures can be categorized?
2. How to define reliability and failure profile concepts for the bridge structures? I.e. when does a bridge fail?
3. Categorize the bridges in Trondheim municipality based on the output from question 1 and list their failure profile based on question 2.
4. What are the main failure modes in the failure profile of the bridges with poor and very poor condition performance indicator?

These research questions are answered in chapter 6, "Conclusion and Further Studies".

1.4 SCOPE OF THE PROJECT

The concept of this project is to present the bridge status in Trondheim based on the data from Norwegian Public Roads administration (SVV) and to introduce and discuss the relevant issues based on the results. Furthermore, the bridges with poor and very poor status are discussed in more detail. This understanding can lead to the development of operation, maintenance and inspection plans considering reliable, safe and cost-efficient approaches.

The scope of the work are listed below:

1. Categorize the bridge structures from different perspectives, including:
    - Material types
    - Age
    - Span height, length and /or headroom
    - Portability
    - Structure forms (design and construction).
    - Environment
    - Inspection assessment
    - Condition indicators
    - Applications and load type
    - Route supported and obstacles crossed
2. Describe the reliability and failure profile in bridge structures, including;
    - Lifetime performance characteristics, reliability and failure
    - Failure causes
    - Failure and deterioration mechanisms
    - Failure modes
    - Failure type
3. Case study for further discussions about the mentioned concepts and more detailed discussions regarding the bridges with poor and very poor status.

1.5 MOTIVATIONS

This report is written based on the following motivations:

1. Describe the definition of failure and reliability from structural perspective and their importance.
2. Provide an overall review regarding the bridge status in Trondheim, including the bridges with poor and very poor status.
3. Show how this information can be utilized not only in research studies but also in practical cases.

4. Personal interests in the field of maintenance and inspection, especially in civil and bridge engineering, made me to follow my supervisor's recommendation for the specialization project and the master thesis.

1.6 PROJECT LIMITATIONS

The limitations faced in this project could be categorized as three above groups:

i) General limitations:
   - It is expected that the reader has the basic knowledge in the civil and bridge structures, inspection and maintenance.
   - In case of having more time for this project, it could be possible to discuss and analyze more concepts to broaden the research perspectives and also to study the discussions more in depth.

ii) Literature study limitations: The limitations regarding the literature study is explained in chapter 2 (under title 2.3 – Limitations).

iii) Case study limitations: The limitations regarding the case study is explained in chapter 4 (under title 4.2 – Case Study limitations, assumptions and possible source of errors).

1.7 REPORT STRUCTURE

The report has been written in four main parts in order to achieve the main objectives of the projects. The content of each part is explained below.

Part 1: INTRODUCTION

The first part contains the main basic information about the project report and an overview of the concepts and approaches.

Chapter 1. Introduction:

- Provide an introduction regarding the background, objectives, motivations and limitations of the research project.
- Explain about how the report is structured.
- Describe the main research questions.

Part 2: LITERATURE REVIEW

In the 2nd part, the literature study is explained in chapter 2 and 3 as explained below.

Chapter 2. Bridge Characteristics and Elements:

- Provide introduction regarding the literature study.
- Categorize the bridge structures from different perspectives.
- Introduce the bridge elements based on different bridge structures.
- Explain the importance of each characteristics in reliability and failure profile.

Chapter 3. Description of Reliability and Failure Profile in Bridges:

- Explain the lifetime performance characteristics, reliability and failure concepts in the bridge structures.
- Describe different failure causes, failure and deterioration mechanisms, failure modes and different failure types.

Part 3: CASE STUDY

The third part of the report is based on literature study and different mentioned concepts which are used for the case study.

Chapter 4. Case Study: Bridges in Trondheim Municipality:

- Shows how to utilize the literature study in a practical case study.
- Discussion about the overall results and the bridges with poor and very poor status.

Chapter 5. Discussion:

- Review and discuss about the case study results from different perspectives.

Part 4: CONCLUSION AND FURTHER STUDIES

The fourth part of the report is about the conclusion of this master thesis and the possibilities for further research and studies in chapter 6.

PART 2 – LITERATURE REVIEW

CHAPTER 2 – BRIDGE CHARACTERISTICS AND ELEMENTS

2 BRIDGE CHARACTERISTICS AND ELEMENTS

Chapter 2 consists of the explanations regarding the required definitions in bridge engineering. The limitation, scope and objectives of the literature study is also explained in this chapter.

In order to approach the case study, it is required to have a clear understanding regarding different bridge types and elements, and how bridge characteristics are categorized. In literature review, the essential theoretical knowledge in bridge engineering are discussed from different perspectives.

2.1 SCOPE AND OBJECTIVES

The main objective of the literature study is to categorize the bridge characteristics and elements. The scope of the literature study is to provide theoretical information about the topics mentioned below:

1. Introduce the relevant and important terms and definitions.
2. Categorize the bridge structures from different perspectives, including:
   - Material type
   - Age
   - Span / height / headroom / length
   - Portability
   - Structure forms (design and construction)
   - Environment
   - Inspection assessment
   - Condition indicators
   - Applications and load type
   - Route supported and obstacles crossed
3. Describe the reliability and failure profile in bridge structures, including;
   - Lifetime performance characteristics, reliability and failure.
   - Failure causes.
   - Failure and deterioration mechanisms.
   - Failure modes.
   - Failure type.

2.2 LITERATURE STUDY LIMITATIONS

Besides the general and case study limitations, the literature study can also have some limitations which are listed below.

- One of the literature study limitations can be the credibility of the papers, articles and the scientific documents which are already published.
- Inability to discuss all the relevant literature study in depth due to the limited time provided for the research.
- The accessibility to all the relevant scientific literatures is one of the limitations.
- Human limitations to include only specific topics and directions. E.g. different people can take different directions in the same research.

2.3 BRIDGE CHARACTERISTICS AND ELEMENTS

In order to develop an accurate failure profile for a bridge structure, it is important to describe the main parts of the bridges, bridge characteristics and their elements clearly to some extent. Therefore, the objective of this chapter is to explain these concepts to provide a clear picture of a bridge structure from different perspectives.

In this chapter, the major and typical parts of a bridge have been described in four main groups as: i) Superstructure, ii) Substructure, iii) Foundation, and iv) Other basic parts. Other parts which are explained in the following can be considered in the main groups of superstructures, substructures and/ or foundations.

Furthermore, the bridge characteristics are categorized from 10 different perspectives, as:

1. Material type
2. Age
3. Span / height / headroom / length
4. Portability
5. Structure forms (design and construction)
6. Environment
7. Inspection assessment
8. Condition indicators
9. Applications and load type
10. Route supported and obstacles crossed

These characteristics are chosen mostly based on the (IAN 171/12, 2012). Other characteristics are added to cover different perspectives of a bridge structure which may be useful for the further researches and discussions in the project. Figure 2-1 shows how different characteristics can be involved together and it could be important for engineers in the process of construction, inspection and maintenance of a bridge (Man-Chung, 2018).

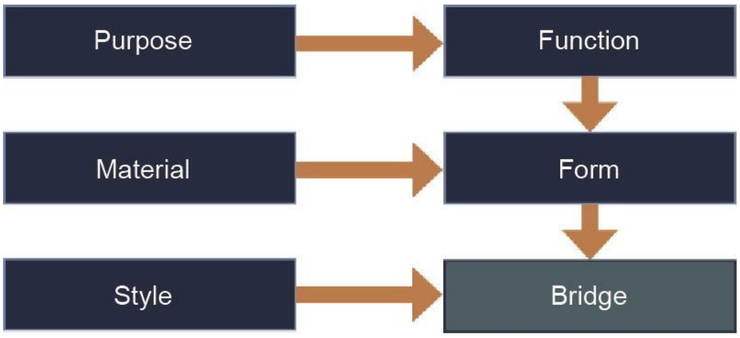

Figure 2-1: Bridge characteristics flow chart (Man-Chung, 2018).

2.4 MAIN AND TYPICAL PARTS OF BRIDGES

The objective of this part is to provide a clear picture of the main and typical parts of a bridge structure. It crucial for a better understanding of the next part which is about the bridge characteristics.

Bridge elements can be defined as the "*Identifiable portions of a bridge made of the same material, having similar role in the performance of the bridge, and expected to deteriorate in a similar fashion*" (NCHRP, 2014).

Bridge structures are divided in four main parts, i) Superstructure, ii) Substructure, iii) Foundation, and iv) Other basic elements (Balasubramanian, 2017). The 4^{th} part, other basic elements, can be included in one of the three main parts.

i. **Superstructure:** "*Superstructure is part of the structure which supports traffic and includes deck, slab and girders. All the parts of the bridge which is mounted on a supporting system can be classified as a Super structure*" (Balasubramanian, 2017).

ii. **Substructure:** "*Substructure that part of the structure, i.e. piers and abutments, which supports the superstructure and which transfers the structural load to the foundations"* (Balasubramanian, 2017).

iii. **Foundation:** *"Foundation is the component which transfers loads from the substructure to the bearing strata. Depending on the geotechnical properties of the bearing strata, shallow or deep foundations are adopted. Usually, piles and well foundations are adopted for bridge foundations*" (Balasubramanian, 2017).

iv. **Other basic parts:**

- **Deck-** "*Deck is the bridge floor directly carrying traffic loads. Deck transfers loads to the Girders depending on the decking material*" (Balasubramanian, 2017).
- **Span-** "*The distance between two bridge supports, whether they are columns, towers or the wall of a canyon*" (Balasubramanian, 2017).
- **Beam-** "*A rigid, usually horizontal, structural element*" (Balasubramanian, 2017).
- **Beam / Girder-** "*Beam or girder is that part of superstructure which is under bending along the span. It is the load bearing part which supports the deck*" (Balasubramanian, 2017).
- **Bearing-** "*Bearing transfers loads from the girders to the pier caps*" (Balasubramanian, 2017).
- **Pier-** "*A vertical supporting structure, such as a pillar"* (Balasubramanian, 2017).
- **Pier Cap / Headstock-** "*Pier Cap / Headstock is the component which transfers loads from the superstructure to the piers. Pier cap provide sufficient seating for the Bridge girders*" (Balasubramanian, 2017).
- **Pile cap and Piles-** "*Pile foundation is the most commonly used foundation system for bridges. Pile is a slender compression member driven into or formed in the ground to resist loads. A reinforced concrete mass cast around the head of a group of piles to ensure they act together and distribute the load among them it is known as pile cap"* (Balasubramanian, 2017).

Figure 2-2 and 2-3 show the main and typical parts in a bridge structure. In table 2-1, some elements significant to structural integrity are mentioned. (Note that this table excludes foundations).

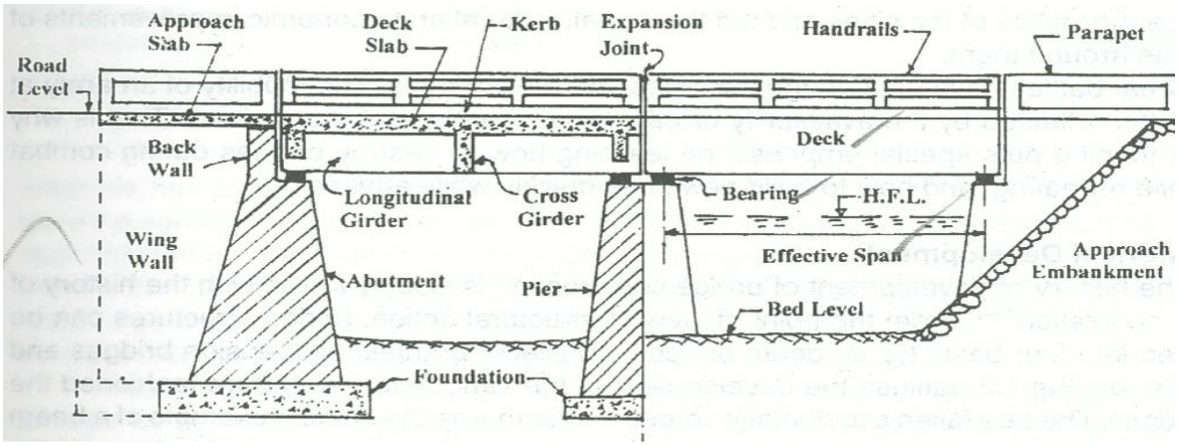

Figure 2-2: Components of a typical bridge (John, 2013).

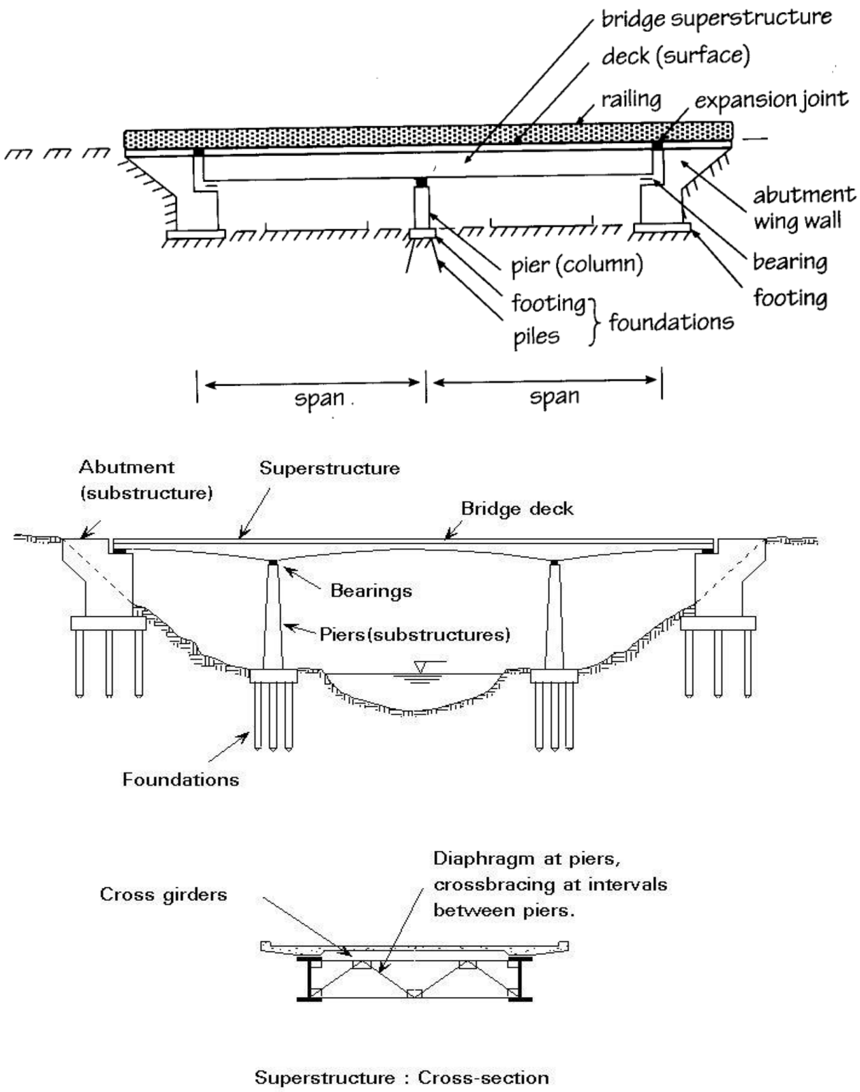

Figure 2-3: Typical bridge elements (Basic Bridge Terms, 2015).

Table 2-1: Elements Significant to Structural Integrity (TfL, 2011).

Structure Type	**Elements Significant to Structural Integrity (excludes foundations)**
Bridge	• Primary deck element • Transverse Beams • Secondary deck element • Half joints • Tie beam/rod • Parapet beam or cantilever • Deck bracing • Abutments (incl. arch springing) • Spandrel wall/head wall • Pier/column • Cross-head/capping beam • Bearings
Cat Lighting	See 'Mast' Group below
Chamber	See 'Bridge' Group above
Culvert	See 'Bridge' Group above
Footbridge	See 'Bridge' Group above
Gantry	• Truss/beams/cantilever • Transverse/horiz. bracing elements • Columns/supports/legs • Base connections • Support to longitudinal connection
Mast	Mast Base Connection
Pipe subway	See 'Bridge' Group above
Retaining Wall	• Retaining wall (Primary/Secondary) • Parapet beam/plinth • Anchoring system
River walls	See 'Retaining Wall' Group above
Subway	See 'Bridge' Group above
Tunnel	See 'Bridge' Group above
Vault	See 'Bridge' Group above

2.5 BRIDGE CHARACTERISTICS

This part explains different bridge characteristics. Bridge characteristics can be important because they can affect the failure profiles of the bridge in different ways. Table 2-2 shows the bridge characteristics explained and categorized. It is inferred from the table that each category can provide information regarding the different aspects of a bridge. For instance, material type, age, span height, length and /or headroom portability and bridge forms or design can provide information regarding the bridge structure type. More detailed information regarding each group is provided in the following.

Table 2-2: Type of information provided by each category regarding a bridge structure (IAN 171/12, 2012).

NO. AND NAME OF THE CATEGORY	TYPE OF INFORMATION
1. Material type 2. Age 3. Span height, length and /or headroom 4. Portability 5. Structure forms (design and construction)	Structure type
6. Environment (Including exposure to scour, flooding, icing, cold climate and deicing materials e.g. salts)	Environment
7. Inspection assessment (including visual accessibility, latent defects and other assessments of the bridges)	Inspection/ Assessment
8. Condition indicators (Including inspector’s condition rating and condition performance indicators)	Condition
9. Applications and load type 10. Route supported and obstacles crossed	Consequence

2.5.1 MATERIAL TYPES

Different material can deteriorate with different rates. So, basic material can affect the deterioration probability in the whole bridge structure. The data regarding the basic materials and their deterioration probability can be found in the historical data or the judgments of experts who have great deal of experiences in the area (IAN 171/12, 2012). It can also be possible to find the relevant information regarding the structure material in the inventory and structure files (IAN 171/12, 2012).

However material types can be a very detailed concept, in this project the material types are explained generally and it includes only the basic materials. It is worth mentioning here that it can be possible that different elements or group of elements in a bridge structure are made of different materials. This issue has been neglected in our study. The most common material types can be named as : i) natural material, ii) concrete, iii) steel and iv) others.

i) Natural material

Natural materials can be used often in bridge structures because of their environmental friendliness. Wood or timber can be named as the good examples of natural material which have been used many bridge structures. (Malo, 2015) .

ii) Concrete

Concrete material can be used in different kinds such as *"insitu mass concrete"*, *"insitu prestressed concrete"*, *"insitu reinforced concrete"* and *"precast prestressed concrete"* (IAN 171/12, 2012).

iii) Steel

Same as concrete material, steel can also be found in different forms e.g. corrugated rolled Steel.

iv) Others

This category can include different types of material. Aluminium, plastic, advanced material, FRP (Fibre Reinforced Polymer) and combination of the materials explained earlier and some new materials such as carbon fibres, ultra-high-performance concrete, and Nano materials are the most important examples in this category (Man-Chung, 2018).

2.5.2 AGE

One of the important bridge characteristics is age. Age of the bridge can have impact on the deterioration of the bridge structures and elements. Higher age can increase the likelihood and rate of the deteriorations. Therefore, it can increase the need for more frequent maintenance and inspection. In the new bridges, initial teething can be considered as the most common problem. After initial teething, bridge is expected to start with its optimal performance. (IAN 171/12, 2012). Bridge age can be found based on equation 4.1. Information regarding the construction year of the bridge can be found on the inventory and structure files (IAN 171/12, 2012).

$$\text{Bridge age} = \text{Current year} - \text{Construction year} \qquad (2\text{-}1)$$

2.5.3 SPAN HEIGHT, LENGTH AND /OR HEADROOM

Span height, length and headroom have been explained and shown in the main and typical bridge parts earlier. The statistical analysis shows that the "long-span bridges" and "retaining walls with greater retained heights" not only more severely fail, but also they are more likely to fail compared to other bridge or structure types (IAN 171/12, 2012). In other words, both the likelihood and consequence of the failure are higher for these types of structures (IAN 171/12, 2012). Table 2-3 shows how span length or height can increase the failure magnitude both in local damage and structure collapse (TfL, 2011).

Information regarding the span, height, headroom and length of the bridge can be found on the inventory and structure files (IAN 171/12, 2012).

Table 2-3: Magnitude of Failure Score, MoF (TfL, 2011).

	Span length or height			
Extent of failure	**<=3**	**>3 to <=10**	**>10 to <=25**	**>25**
Local damage	10	10	10	10
Structural collapse	40	45	65	85

2.5.4 PORTABILITY

Bridge structures can be categorized based on their portability, if they are moveable, fixed or temporary. Portability can be neglected in some of the relevant standards and assessments.

i. **Moveable:** Moveable bridges are built with moveable decks. The decks are normally moved and controlled by electricity. (Balasubramanian, 2017).
ii. **Fixed:** Fixed bridges are considered as the most common type of bridges. They are not built with moveable parts, and their design intention is to stay in the built locations (Balasubramanian, 2017).
iii. **Temporary:** Temporary bridges can be moved to diverse locations by using different machinery types. This type of bridges can be commonly used in military (Balasubramanian, 2017).

2.5.5 STRUCTURE FORMS AND DESIGNS

Engineers have built bridges in different structural forms. Bridges and structures in different forms can deteriorate with different rates and degrees (IAN 171/12, 2012). Bridge structures are divided into different groups based on the forms of forces which are distributed on their structures. Figure 2-4 briefly shows the most common categories and the relevant forces. Based on the information in this part, the bridge elements are explained in the next part using pictures. Using pictures helps in providing a visual understanding about the different bridge forms and elements. Information regarding the structure form can be found on the inventory and structure files (IAN 171/12, 2012).

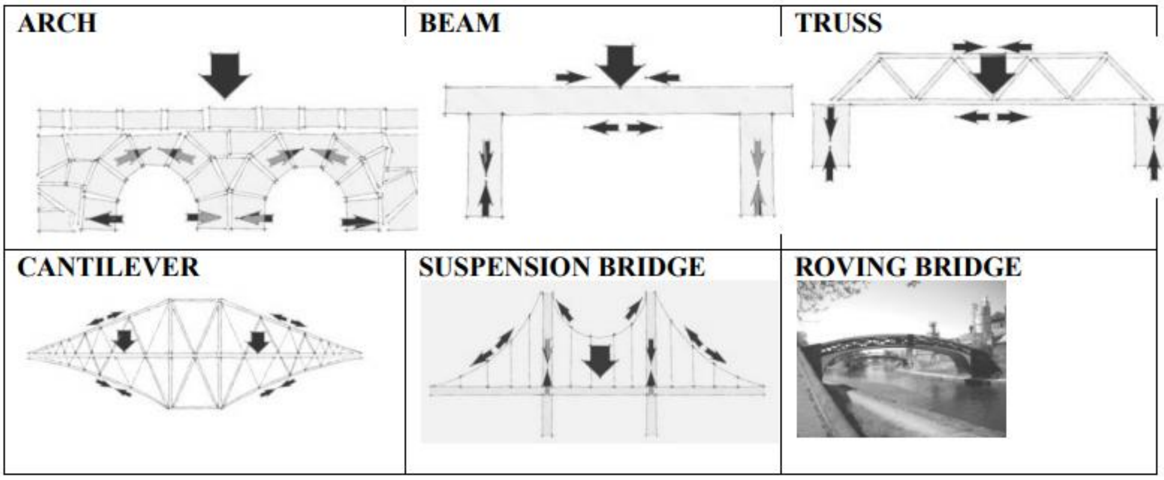

Figure 2-4: Structure forms and the associated forces (Balasubramanian, 2017).

Bridge forms can be categorized and listed below based on their design and construction forms.

- **Arch:** Arch bridges are popular for their strength and attractive design. The reason for the great strength is the form of arch in their design and construction. Various types of materials can be used in building arch bridges (Bridges and Structures, 2009). Figure 2-5 shows Danhe Bridge which is an example of arch bridges. In table 2-4, the main pros and cons of arch bridges are discussed and presented.

Figure 2-5: Danhe bridge as an example of an arch bridge (Janberg, 2016).

Table 2-4: Pros and cons of arch bridge structures (ScienceStruck, 2018) (Bridges and Structures, 2009).

Strengths (Pros)	Weaknesses (Cons)
• Wide range of options in building materials. • Attractive. • High resistance and very strong. • Strengthen with Usage.	• Quite expensive. • Design and location limitations. • Limited Span Length. • Long Construction Time. • Maintenance is Needed Long.

Figure 2-6 shows the elements and parameters used in arch bridge structure. The parameters are explained below and the description is applicable to other bridge forms as well. Therefore, these descriptions are not repeated in the next brigde and forms.

- C: Compression (Pushing or pressing force)
- T: Tension (Pulling or stretching force)
- R: Reaction (Sum of tension or compression force)
- LL: Live load (Force of people or vehicles using bridge- variable and removable uniform load)
- DL: Dead load (Force due to self-weight of bridge materials used – uniform load always there)
- w: Total uniform load

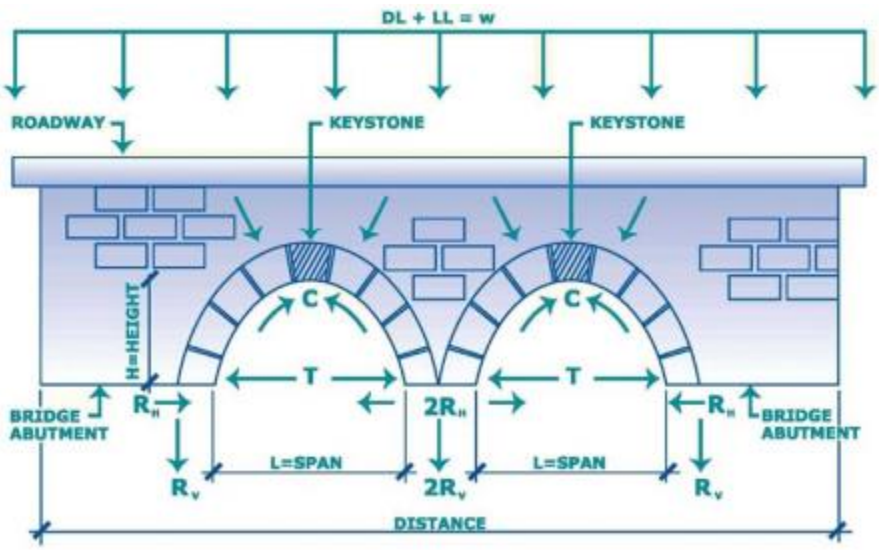

Figure 2-6: Elements and parameters used in arch bridge structure (Bridges and Structures, 2009).

- **Beam:** Beam bridges can be considered as the oldest bridge forms. It is simple and common to be built. The strength of a beam bridge is highly dependent on the strength of the roadway and additional piers. Usually beam bridges have long length and short span (Bridges and Structures, 2009). Figure 2-7 shows Albert Memorial Bridge which is an example of beam bridges. In table 2-5, the main pros and cons of beam bridges are discussed and presented. Figure 2-8 shows the elements and parameters used in beam bridge structure.

Figure 2-7: Albert Memorial Bridge as an example of beam bridge (Historic Albert Memorial Bridge, 2015).

Table 2-5: Pros and cons of beam bridge structures (Leonhardt, 1984) (Kevin-F, 2018) (Balasubramanian, 2017).

Strengths (Pros)	Weaknesses (Cons)
• Designed for Short Span • Placing Beams on the Piers • Simple and common to make • Inexpensive	• Impractical for Long Spans • Drooping Effect • Low possibility of passing vehicles from under it

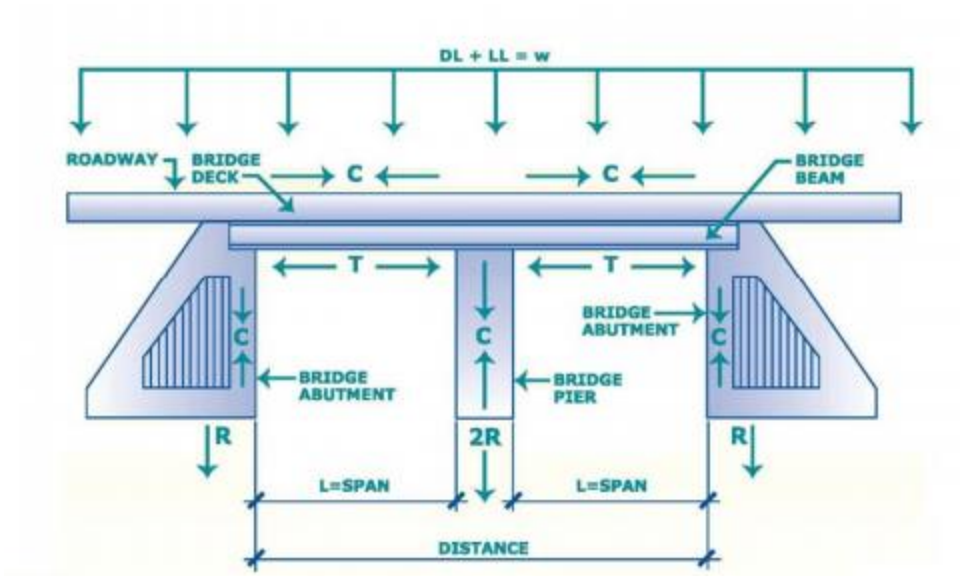

Figure 2-8: Elements and parameters used in beam bridge structure (Bridges and Structures, 2009).

- **Truss:** Truss is "*a rigid frame composed of short, straight pieces joined to form a series of triangles or other stable shapes"* (Balasubramanian, 2017). Truss bridges have great strength. Therefore, there are commonly used as railway bridges (Bridges and Structures, 2009). Figure 2-9 shows Józef Piłsudski Bridge which is an example of truss bridge type. In table 2-6, the main pros and cons of beam bridges are discussed and presented. Figure 2-10 shows the elements and parameters used in truss bridge structure.

Figure 2-9: Józef Piłsudski Bridge as an example of truss bridges (Kramarczik, 2013).

Table 2-6: : Pros and cons of truss bridge structures (Balasubramanian, 2017).

Strengths (Pros)	**Weaknesses (Cons)**
• Great strength. • High efficiency in material use.	• Complex to build. • High need of maintenance.

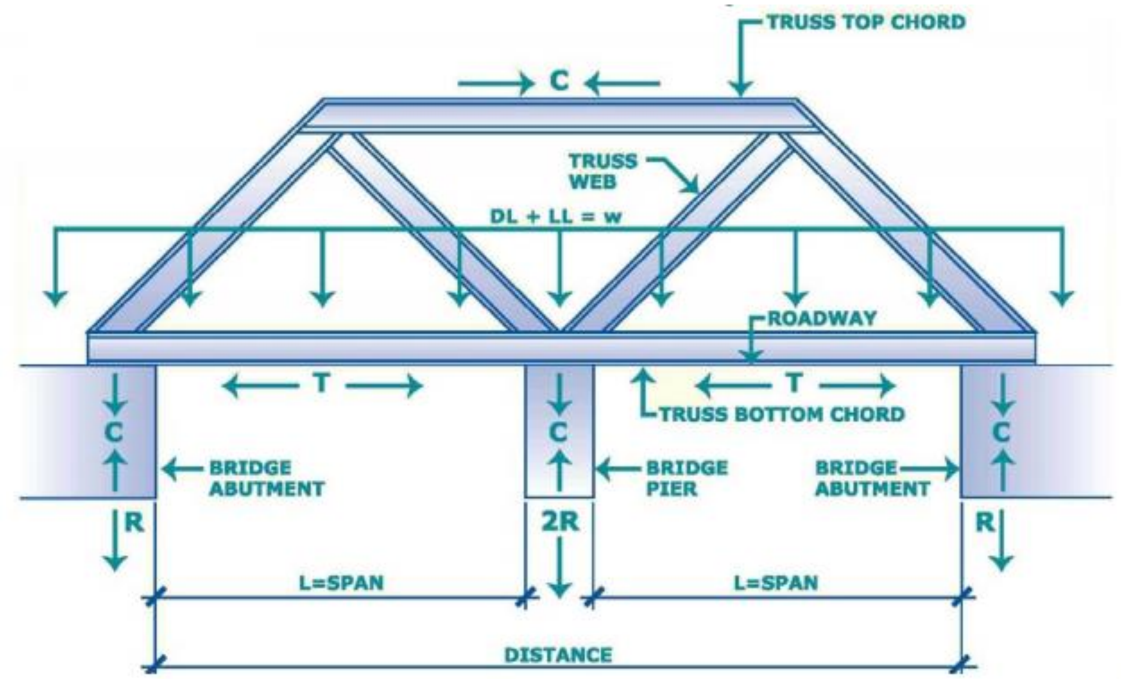

Figure 2-10: Elements and parameters used in truss bridge structure (Bridges and Structures, 2009).

- **Cantilever:** Cantilever bridges look like a spring board. Figure 2-11 shows Albert Memorial Bridge which is an example of truss bridges. In table 2-7, the main pros and cons of cantilever bridges are discussed and presented.

Figure 2-11: The forth bridge as an example of cantilever bridges (McBey, 2015).

Table 2-7: Pros and cons of cantilever bridge structures (Balasubramanian, 2017).

Strengths (Pros)	**Weaknesses (Cons)**
• Easier to be built when crossing difficult obstacles.	• Complex • Difficult maintenance

- **Suspension:** Suspension forms can be considered as strong bridges and they can be used for long span. The main elements in a suspension bridge is a pair of cables over two towers (Balasubramanian, 2017). Figure 2-12 shows Golden Gate Bridge which can be one of the most famous examples of suspension bridges. In table 2-8, the main pros and cons of suspension bridges are discussed and presented. Also, Figure 2-13 shows the elements and parameters used in this kind of bridge structure.

Figure 2-12: Golden gate bridge as an example of suspension bridges (Bierman, 2017).

Table 2-8: Pros and cons of suspension bridge structures (Balasubramanian, 2017).

Strengths (Pros)	**Weaknesses (Cons)**
• Great strength • Long span	• Expensive • High complexity in construction • Long building time • Require a large amount of material

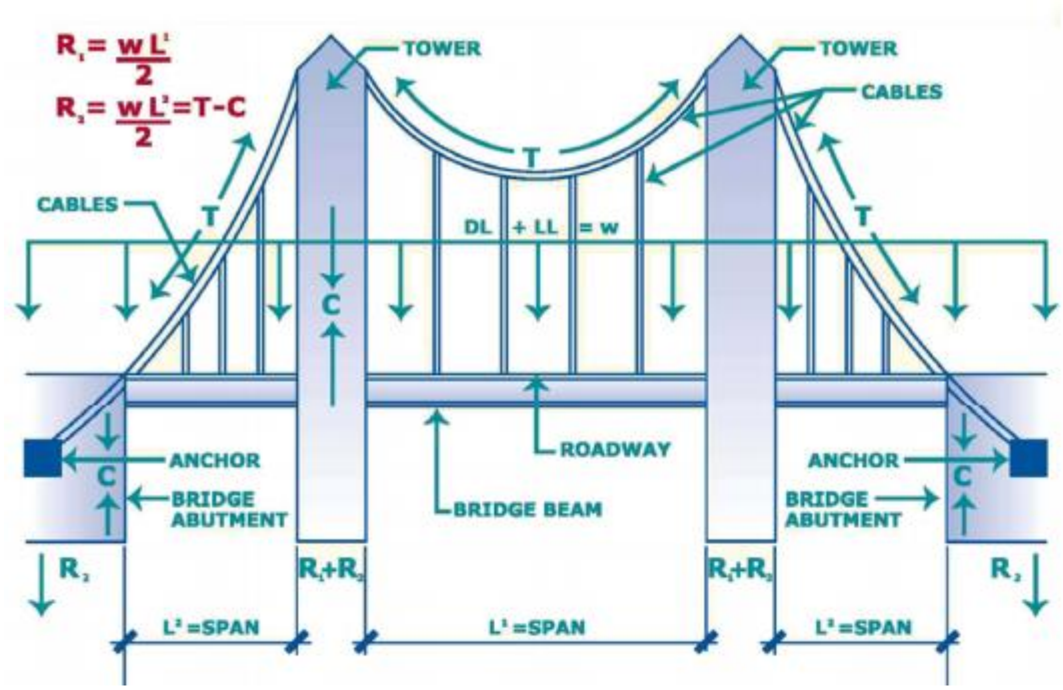

Figure 2-13: Elements and parameters used in suspension bridge structure (Bridges and Structures, 2009).

- **Cable-stayed:** *This type of bridges has one or more towers, each of which anchors a set of cables attached to the roadway*. It can be possible to develop new materials and technique on this type of bridge (Balasubramanian, 2017). Figure below shows Mohammed VI Bridge as an example of cable-stayed bridges. Disadvantage and advantages of cable-stayed bridges are listed in table 2-9 and figure 2-15 shows the elements and parameters used in truss bridge structure.

Figure 2-14: Mohammed VI Bridge as an example of cable-stayed bridges (FEZ, 2016).

Table 2-9: Pros and cons of cable-stayed bridge structures (Balasubramanian, 2017).

Strengths (Pros)	Weaknesses (Cons)
• Better stiffness compared to suspension bridge. • Economical way to span long distances • Reasonable for medium spans bridges. • Possibility of using cantilevering • No need for large ground anchorages.	• More costly compare to other bridge forms, except suspension bridges.

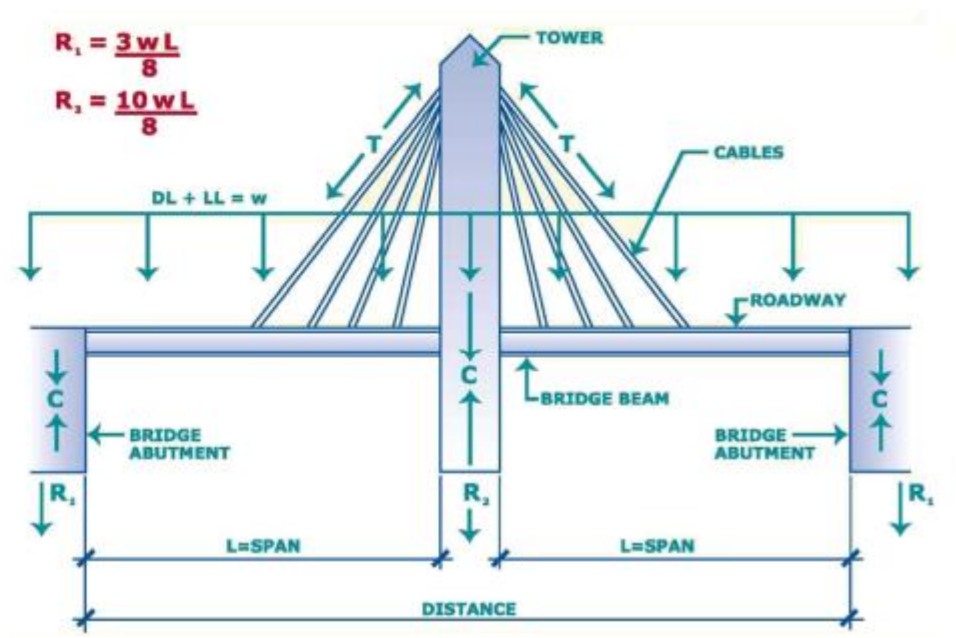

Figure 2-15: Elements and parameters used in cable-stayed bridge structure (Bridges and Structures, 2009).

Besides the six-structure design explained earlier, there can be four design descriptions. These descriptions can be combined with the mentioned design forms, e.g. it can be possible to have an arch culvert bridge.

- **Culvert:** Culvert bridge is type of bridge which allows the traffic to pass both under and on the bridge. Figure 2-16 shows an example of a culvert bridge (Rahman, 2018). There can be different culvert bridge e.g. combing with the bridge forms. Figure 2-17 illustrates the four type of culvert bridges. Disadvantage and advantages of culvert bridges are listed in table 2-10.

Figure 2-16: Example of a culvert bridge (Northwest Consultants, 2019).

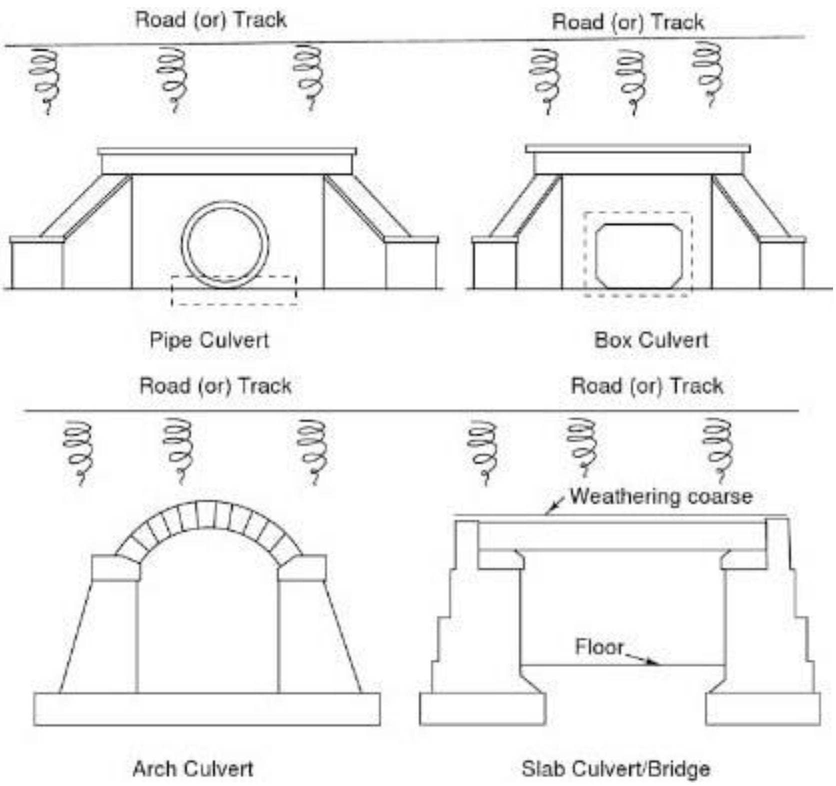

Figure 2-17: Typical Sections of Different Types of Culverts (Arjun, 2018).

Table 2-10: Pros and cons of uniform box or tubular culvert bridge structures (OFFICE OF STRUCTURES, 2011).

Strengths (Pros)	Weaknesses (Cons)
• *"Most culverts require very little, if any, structural maintenance".* • *"Scour is localized, more predictable and easier to control".* • *"Usually quicker and easier to build".* • *"Frost and ice usually do not form on the traveled way before other areas experience the same problem".*	• *"Roadway susceptible to overtopping and possible breaching of embankment if culvert clogs with drift, ice or debris".* • *"Loss of sunlight and changed flow conditions can significantly reduce viability of stream for habitat within the limits of the culvert".*

- **Framed Span:** Sometimes engineers use the different type of frame on the bridge span. This type of bridge can be called framed span bridges. E.g. it can be possible to have a framed span beam bridge structure.

- **Slab Flat:** This type of bridge is designed and built with straight and flat slabs. Flat slabs can be helpful in the bridges with short spans and the slab can be built in two types as: i) Solid and ii) Voided (Bridge types, 2018).

- **Simply Supported:** this type of bridge has hinged support in different part of the bridge, normally at ends. E.g. a simply supported beam bridges falls into this type.

2.5.6 ENVIRONMENT

The environmental factors can be considered as one of the bridge characteristics because they can influence the deterioration mechanism and rate in different bridge structures. There are three main exposure factors which needs to be considered.

i. Exposure to scour

Some of the bridges can be considered as susceptible structures to scour exposure. It is not proper for these structures to decrease the inspection interval. Information regarding the scour exposure of the structures can be found based on the inventory, structure files and scour assessments (IAN 171/12, 2012).

ii. Exposure to flooding

Bridge structures can also be located in places with a high possibility of flooding. Flooding can increase the failure risk which can be considered in the different assessments. Information regarding the flooding exposure on the structures can be found in the environment agency records and qualitative assessment of the flooding probability or likelihood in the area (IAN 171/12, 2012). The qualitative assessment is normally performed based on the data available in the relevant data bases.

iii. Exposure to icing, cold climate and deicing materials e.g. salts

Icing, cold climate and deicing materials like salt can increase the deterioration rates in bridge structure. Information regarding the exposure to these factors can be found in the environment agency records and qualitative assessment of the icing probability or likelihood in the area (IAN 171/12, 2012). It is also possible to find the deicing material used for the structures in the relevant data bases.

Table 2-11 shows an overall description regarding these environmental exposures and it is also described what the potential results from the exposure can be.

Table 2-11: Exposure desxcription and severity (TfL, 2011).

Exposure severity	Exposure description	Examples
Mild	Structure and/or elements of a structure: Generally exposed to mild weather conditions, i.e. may be sheltered or in an environment that results in little or no exposure to severe weather conditions; and Not exposed to any aggressive agents, e.g. no exposure to road de-icing salts or 10 m away from traffic spray, not exposed to or buried in aggressive soil agents, no exposure to contaminated water, etc.; and With no ventilation or condensation problems or where poor ventilation or the level of condensation are unlikely to increase the rate of deterioration.	Elements protected from salt spray with cladding or by a protective enclosure. Deck soffit and piers of integral bridges where the obstacle crossed is not a road, i.e. elements are not subjected to spray from salted road. Tenanted arch bridges. Half-joints or hinge joints overlaid with functional expansion joints

Exposure severity	Exposure description	Examples
Moderate	Structure and/or elements of a structure exposed to: Moderate (normal) weather conditions, e.g. direct rain, moderate humidity or condensation, some freeze-thaw action etc.; and/or Moderate de-icing salt spray and airborne chlorides; e.g. within 3 to 10m of traffic spray on routes with de-icing salts; and/or Low to moderate river flow. But elements are not exposed to or buried in aggressive soils that are contaminated with acidic water or water containing sulfates.	Top of roadside bridge pier or abutment subject to light vehicle spray from salted road. Bridge deck soffit subject to light vehicle spray from salted road. Structural elements, e.g. piers, subjected to abrasion/erosion.
Severe	Structure and/or elements of a structure exposed to: Continuous or regular severe/extreme weather conditions, e.g. hot and cold extremes, high freeze-thaw action, severe humidity or condensation, etc.; and/or Severe de-icing salt spray, e.g. within 3m of traffic spray on routes with de-icing salts; and/or Run-off and/or ponding on routes with deicing salts; and/or Aggressive soils, i.e. completely or partially buried in aggressive soils that are contaminated with acidic water or water containing sulfates. Medium to rapid river flow and flooding.	Roadside bridge abutment, Parapet upstand or deck edge beam subject to heavy vehicle spray from salted road. Section of bridge deck near a leaking expansion joint or gutter, e.g. deck end or crosshead. Half joints or hinge joints overlaid with non-functional expansion joints. Top surfaces of unwaterproofed bridge decks. Areas where corrosion or spalling of surface concrete is evident. Structural elements, e.g. piers, susceptible to scour.
Very severe	Structure and/or elements of a structure exposed to: Marine environment and/or abrasive action of sea water or completely immersed in sea water; and/or Tidal splash and spray zone; and/or Airborne salt but not in direct contact with sea water; and/or Corrosive fumes in industrial areas	Surfaces directly affected by sea water spray, e.g. surfaces adjacent to the sea Surfaces directly affected by airborne salts, e.g. deck, walls, parapet edge beams, etc. Completely/partially submerged marine structures Structures near to or on coastal areas Structures in industrial areas with high humidity and aggressive atmosphere

2.5.7 INSPECTION ASSESSMENT

Inspection assessment is crucial to show different perspectives of bridge structure characteristics and their performance. Inspection assessment are considered in 3 different categories and explained below. Each of these categories can be rated and considered independently.

i. Visual accessibility

Visual accessibility can have close relation to the reliability of the general inspection. More limitations in visual accessibility can reduce the reliability of this kind of inspection. The relevant data can be found in qualitative assessment of visual accessibility (IAN 171/12, 2012).

ii. Latent defects

Latent defects cannot be discovered in some structures during the principal inspection which can affect reliability and deterioration rate. Information regarding the latent defects of the structures can be found based on the inventory and structure files (IAN 171/12, 2012).

Table 2-12 shows the importance of visual accessibility and latent effects in further considerations in maintenance and inspection planning of the structure. The effect of having one or more not visible elements can increase the inspectability score by 20 times. Inspectability can be defined as "*if the necessary information about the condition of the structure(s) and any significant safety concerns be readily obtained without any access difficulties"* (TfL, 2011).

iii. Assessments

Different assessments can discover various load effects and degrees of freedom in a specific structure. Information regarding the assessments of the structures can be found based on *"the load management records", "assessment reports"* and *"interim measures records*" (IAN 171/12, 2012).

Table 2-12: Inspectability Score, IS (TfL, 2011).

Inspectability Consideration	Score
All elements significant to structural integrity (Except foundation) are visible (not hidden) and can be adequately inspected during a general inspection.	0
One or more element(s) significant to structural integrity (Except foundation) are not visible or hidden and/or cannot be adequately inspected during a general inspection.	20

2.5.8 CONDITION INDICATORS

Condition indicators can provide more details regarding the performance of the bridge structure. These indicators can be categorized into two criteria explained below. Each of these categories can be rated and considered independently.

i. Inspector's condition rating

Inspectors can evaluate the bridge condition based on the inspection records and subjectively rate it based on different categories e.g. the categories can be qualitatively defined as "good, fair or poor". This rate can provide beneficial rates regarding the overall bridge condition (IAN 171/12, 2012).

ii. Condition performance indicators

Condition performance indicators can be included in the bridge characteristics if the relevant data are available for it. It is an objective indicator which can be scored (e.g. between 0 and 100) and can provide information regarding the physical condition of the bridge (IAN 171/12, 2012). The relevant data can be found in condition performance indicator reports and they can be classified into two groups:

1. Average Condition PI Score, PIAv (based on all elements).
2. Critical Condition PI Score, PICrit (based on the most critical elements only).

2.5.9 APPLICATIONS AND LOAD TYPE

Application and load types provide information regarding the failure consequence of a bridge structure on the whole transportation or road network system. The Information regarding the applications and load type can be found based on the *"load management records", "assessment reports" and "interim measures records*". (IAN 171/12, 2012).

- Military
- Cycleway
- Pedestrian
- Railway
- Ferry ports
- Pipeline
- Aqueduct
- Commercial
- Support structure
- Double-decked (Multi-purpose).
- Motorway (including full highway and heavy Load Route)

2.5.10 ROUTE SUPPORTED AND OBSTACLES CROSSED

Route supported and obstacles crossed show the criticality of the bridge failure in relation to the whole transportation or road network system. In other words, it shows how the whole transportation or road network system can be affected in case of bridge failure e.g. collapse. The Information regarding the route supported and obstacles crossed can be found in the inventory information (IAN 171/12, 2012).

There are different types of route supported and obstacles crossed which can be listed as below:

- Road type A.
- Road type B.
- Cycleway.
- Pedestrian.
- Motorway.
- Railway.
- Access or minor routes.
- Disused places.
- Natural grounds.
- River or water.
- Canals.

Table 2-13 shows the importance of both route supported and obstacles crossed in socio-economic aspects of a bridge structure

Table 2-13: Socio-Economic Importance Score, SEIs (TfL, 2011)

		Route supported by or adjacent to the structure			
Obstacle crossed by the structure	**Extent of failure**	**Disused**	**Unclassified, cyclist and pedestrian**	**B and C class roads**	**A class / Principal roads**
	Waste ground / disused / non-navigable watercourse	090	20	30	50
	Unclassified, cyclist and pedestrian	10	30	50	70
	B and C class (local access/ distributer) roads and business premises	30	50	70	90
	Navigable watercourse and A class / Principal roads	50	70	90	110
	Railways	70	90	110	120

2.6 SUMMARY OF BRIDGE CHARACTERISTICS

In order to have an overall summary of the important mentioned characteristics, the risk assessment criteria recommended in (IAN 171/12, 2012) can be used. Table 2-14 shows this risk assessment criteria.

In the case study, this data sheet is used in order to standardize the gathered information from Norwegian Public Roads Administration - Statens vegvesen (SVV) into a general format which can used for further potential researches and assessments.

Table 2-14: Risk assessment criteria (IAN 171/12, 2012).

ASSESSMENT CRITERIA	COMMENTARY	SOURCE OF INFORMATION
Structure Type		
Form	Different structural forms can be expected to experience varying degrees of deterioration and have each been rated accordingly to consider this.	(a) Inventory (b) Structure File
Material	The primary constituent material will have an impact on the likelihood of deterioration. Historical performance has been evaluated for different construction materials and is reflected in the scoring.	(a) Inventory (b) Structure File
Age	The age of a structure will usually affect the likelihood and rate of deterioration. In general, it would be expected that an older structure approaching the end of its design life will encounter more maintenance issues and hence be more prone to deterioration. Newer structures may encounter initial teething problems before they are considered to be performing optimally.	(a) Inventory (b) Structure File
Span / Height / Headroom / Length	Although every structure has different design requirements, probabilistic analysis shows that bridges with longer spans and retaining walls with greater retained heights, tend to be at a higher risk of failure. Not only is the likelihood increased but also the associated consequence of failure.	(a) Inventory (b) Structure File
Environment		
Scour	Scour susceptible structures are not suitable for reduced inspection intervals.	(a) Inventory (b) Structure File (c) Scour Assessment in accordance with BA 74/06 or BD 97/12
Flooding	Structures in areas susceptible to flooding should be assessed as having increased risk.	(a) Qualitative assessment of the available information that would inform the likelihood of flooding (b) Environment Agency records
Inspection / Assessment		
Visual Access	Limited visual accessibility to critical elements will reduce the reliability of the General Inspections undertaken between Principal Inspections.	(a) Qualitative assessment of the available information on visual accessibility.
Latent defects	Some structure types are more susceptible to containing defects that are not evident during a Principal Inspection for example, post-tensioned concrete bridges with internal grouted tendons.	(a) Inventory (b) Structure File

ASSESSMENT CRITERIA	COMMENTARY	SOURCE OF INFORMATION
Assessments	Where an assessment has been carried out on a structure, a greater degree of confidence can be achieved with regard to the structure's ability to carry load. The findings of the assessment report should give a clear indication of any current load restrictions and any recommended condition factors. Any current load restrictions in place indicate that the current condition of the bridge is below design standard, resulting in a higher potential risk of deterioration.	(a) Load Management Records (b) Assessment reports (c) Interim Measures Records
Condition		
Inspector's Condition Rating	Condition is to be assessed using two criteria. The first is the Inspector's subjective condition rating of the structure (ie. Good, Fair or Poor), which should give a good overview of the condition of the structure.	(a) inspection records
Condition Performance Indicators	Secondly, Condition Performance Indicators, where available, are to be taken into account. These are an objective measure of the physical condition of the highway structures stock, calculated using the Highways Agency's Severity/Extent condition rating system[5]. They are reported for each structure on a scale of 0 to 100, where 0 represents the worst possible condition and 100 represents the best possible condition. There are two scores to consider: 1. Average Condition PI Score, PI_{Av} (based on all elements) 2. Critical Condition PI Score, PI_{Crit} (based on the most critical elements only)	(a) Condition Performance Indicator Reports
Concrete Deterioration	Any deterioration of concrete including that due to Thaumasite Sulphate Attack, Alkali Aggregate Reaction, Alkali Silica Reaction and Alkali Carbonate Reaction should be scored	(a) Inventory (b) Structure File (c) inspection records
Consequences		
Load Type	Load type may not have an impact on the likelihood of deterioration or failure. However, it will have a bearing on the overall consequence of any potential collapse.	(a) Load Management Records (b) Assessment reports (c) Interim Measures Records
Route supported and obstacle crossed	These attributes are intended to reflect the importance of the structure within the overall road network in the event of a structural collapse.	Inventory
Failure Mode	Brittle failure modes can result in collapse without warning and high consequences whereas ductile modes typically give warning of structural distress.	(a) Inventory (b) Assessment reports

CHAPTER 3 – DESCRIPTION OF RELIABILITY AND FAILURE PROFILE IN BRIDGES

3 DESCRIPTION OF RELIABILITY AND FAILURE PROFILE IN BRIDGES

The main objective of this chapter is to provide necessary information to describe the failure profile for different bridges based on the characteristics and the elements explained earlier.

First the life performance characteristics and reliability of the bridge are explained. Further, different concepts in failure profile are discussed. The concepts covered in this chapter can be named as below.

- Lifetime performance characteristics, reliability and failure
- Failure causes
- Failure and deterioration mechanisms
- Failure modes
- Failure type

3.1 LIFETIME PERFORMANCE CHARACTERISTICS, RELIABILITY AND FAILURE

This part is divided into three subsections. The subsections are explained based on the logical order to provide better understanding, but still they are conceptually connected together. The main three subsections are:

- Lifetime performance characteristics
- Reliability
- Failure

LIFETIME PERFORMANCE CHARACTERISTICS: There are different elements and factors which can have influence on the bridge performance and the design service life. Design service life is defined as "*the assumed period for which a structure or a structural member is to be used for its intended purpose with anticipated maintenance, but without substantial repair being necessary"* (ES ISO 2394, 2012).

In order to understand the reliability of the bridge, it is important to have a clear picture of the common and usual lifetime behavior of the bridge components. Similar to other engineering structures, the lifetime behavior of the bridge components can be expected as the bath-tube curve (Applebury, 2011). Figure 3-1 shows bath-tube curve for the expected failure rate of the bridge based on the time. As it can be seen in the figure, there are three important phases in the curve.

1. Infant Morality: This phase is also called the early life of the structure and any defects or flaws in the construction can appear during this phase. Infant mortality rate can have an adverse effect on the expected utilizable period of the structure. Therefore, the inspection and quality controls in the infant mortality phase can be very important (Applebury, 2011).

2. Useful life: After the first phase, the useful life of the structure starts. The failure rate is more stable and therefore the probability of failure is lower when compared to the first phase.

3. Wear-out: The failure and deterioration rate increase during the last phase of the structure life. Therefore, the probability of failure can be higher when compared to the second phase. Monitoring and inspection play even more an important role in this stage to detect any deterioration, and repair and maintenance required.

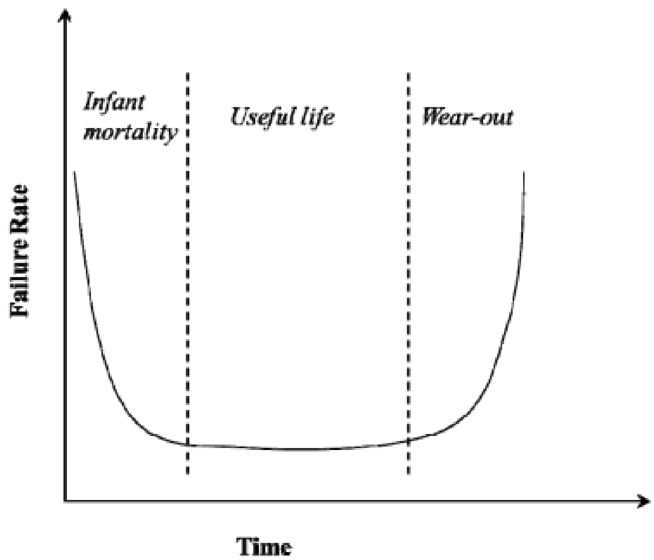

Figure 3-1: Plot of the "bathtub" probability curve. (Applebury, 2011)

Even though this curve can provide an expectation of the lifetime behavior of the bridge, one should keep in mind that there are many factors and elements which can affect the shape and the timeline. Different bridge characteristics and elements described in chapter 4 can be named as these influencing factors (Applebury, 2011). Table 3-1 shows some variables which can be used for probabilistic estimates.

Table 3-1: Variables use for probabilistic estimates of time-varying reliability (Applebury, 2011).

- Concrete cover
- Workmanship
- Concrete strength and modulus
- Reinforcing steel strength and modulus
- Shrinkage of concrete
- Thickness
- Dead load
- Truck live load
- Water-cement ratio
- Corrosion rate
- Crack width
- Critical crack width
- Crack depth
- Cracking density
- Loading rate
- Surface chloride concentration
- Critical chloride concentration
- Chloride diffusion
- Time to corrosion initiation
- Prestress steel strength and modulus
- Prestress losses
- Impact factor
- Area of reinforcing steel and concrete
- Flexural forces
- Shear forces
- Load distribution factors
- Reinforcement spacing

RELIABILITY:

"Reliability is the ability of an element or component to operate safely under designated operating conditions for a designated period of time" (NCHRP, 2014). In other words, *"reliability is the ability of a structure or structural member to fulfil the specified requirements, during the working life, for which it has been designed. Reliability covers safety, serviceability, and durability of a structure"* (ES ISO 2394, 2012). The importance of the reliability increases especially when the complexity rises in the system or any elements.

Equation 3-1 from (Rausand & Høyland, 2004) shows the general reliability definition.

$$R(t) = Pr(T \geq t) \qquad (3\text{-}1)$$

- R (t): Reliability function of an item
- T: Time to failure of the member
- t: Specific functioning time
- Pr (T ≥ t): Probability (Pr) or likelihood that the time to failure of the bridge goes above the specific functioning time

For the structures like bridges, the concept of physical or structural reliability is defined. This concept is dependent upon the physical perspectives of the structure. As shown in equation 3-2 from (Rausand & Høyland, 2004), physical or structural reliability is defined as *"the probability that the strength is higher than the load applied"* (Rausand & Høyland, 2004).

$$R = Pr(S > L) \qquad (3\text{-}2)$$

- R: Reliability function of a bridge/structure member
- S: Strength of the member
- L: Applies load of the member
- Pr (T ≥ t): Probability (Pr) or likelihood that strength is greater than the load.

Reliability can be considered in two levels: i) System reliability, ii) element reliability.

There are the other important definitions in reliability engineering including:

Reliability target – "*Specified average acceptable failure probability that is to be reached as close as possible. Reliability targets are generally model dependent and need to be set for each case considered based on the models used"* (ES ISO 2394, 2012).

Reliability class – "*Class of structures or structural members for which a particular specified degree of reliability is required"* (ES ISO 2394, 2012).

Attributes – *"Characteristics that affect the reliability of a bridge or bridge element"* (NCHRP, 2014).

FAILURE AND DETERIORATION

Failure is generally defined as *“the termination of the ability of a system, structure, or component to perform its intended function”* (NCHRP, 2014). In the bridge structures, failure can be *“the condition at which the specific element is not able perform the required function to safely and reliably carry normal loads and maintain serviceability”* (NCHRP, 2014).

Failure in structural perspectives can also be defined as *“insufficient load-bearing capacity or inadequate serviceability of a structure or structural member, or rupture or excessive deformation of the ground, in which the strengths of soil or rock are significant in providing resistance”* (ES ISO 2394, 2012).

In order to have a simple but specific definition of failure in the bridge structures, it can be defined that a bridge fails when any one of structure elements is not fully or partially functioning. This can lead to a potential risk of damage or harm against human, environment and assets.

One of the most common failure can be due to deterioration in bridge elements. Deterioration can be defined as *“the process that adversely affects the structural performance including reliability over time”. “Deterioration can have different causes e.g. natural elements, chemical, physical, or biological actions, normal or extreme environmental factors and repeated actions such as those causing fatigue, wear due to use, and improper operation and maintenance of the structure”* (ES ISO 2394, 2012).

3.2 FAILURE CAUSES

Different failures can occur due to different causes. Any circumstance or conditions during different life cycle stage of the bridge can result in structure failure. These stages can be included as design, operation, manufacture, installation, use or maintenance (EN 13306, 2010). There are four main failure cause categories which can be named as below. Furthermore, these categories can be considered as the most relevant causes in the bridge engineering concept, and it can be possible that a failure cause would be a combination of one or more of these failure causes

3.2.1 DESIGN FAILURE

Design failures are relevant to the design characteristics of a bridge structure. Material, bridge design and form and other similar characteristics mentioned in chapter 4 can be considered as design failure examples.

3.2.2 CONSTRUCTION FAILURE

Construction failure can be considered as the causes which can happen due to failure in the construction phase and process. E.g. any flaws in the construction phase can lead to construction failures.

3.2.3 AGING FAILURE

Failure causes relevant to aging can be due to three different reasons e.g. environment, load (/local condition) and functions.

Aging failure due to the environment can be named as icing, rain, temperature, frost and the other external environmental factors. Local condition resulting in aging failure can be the local load and condition factors including soil characteristics and abrasion. Function aging failure can be due to the normal usage of the bridge. The elements involved are structure, age and wear and tear due to normal bridge life cycle.

3.2.4 MISHANDLING FAILURE

Any mishandling during the bridge life cycle can be named as mishandling failure causes. For instance, mishandling in maintenance and deicing activities, vandalism and traffic accidents can be mentioned.

3.3 FAILURE AND DETERIORATION MECHANISMS

Failure and deterioration concepts are already explained in this chapter earlier (under the title 5.1). Failure or deterioration mechanism is the process which can cause the damage or failure in the bridge structure or elements. (NCHRP, 2014). I.e. failure mechanism can explain the process or mechanism of a failure cause (EN 13306, 2010). These processes can occur due to different initiation. There are three main failure or deterioration mechanism which can be important in bridge engineering concepts.

3.3.1 CHEMICAL

It is defined as chemical mechanism or process which can result in failure of any bridge elements. Chloride attack, carbonation, corrosion, sulphate attack or other chemical mechanism can be named as the examples of chemical failure or deterioration mechanism.

3.3.2 PHYSICAL

Any physical process or force that can result in bridge failure in any structure level can be considered as a physical failure or deterioration mechanism. For instance, erosion, soil pressure, ice effects, wind and current impact traffic loads and fatigue can be included as the physical mechanism that causes bridge deterioration.

3.3.3 THERMAL

There can be some failure or deterioration due to thermal mechanisms. Temperature cycle and relevant changes in a cycle can be considered as a relevant example of thermal mechanism results in failure.

It is also important to estimate the deterioration rate for the possible mechanisms. Deterioration rate can have a critical impact on the risk assessment, inspection scheduling and maintenance planning (TfL, 2011). Table -2 shows the scores for deterioration rates based on (TfL, 2011), and how they can be categorized into three groups based on the mechanism rapidity. The three groups are named as: i) slow rate of deterioration, ii) medium, and iii) fast rate of deterioration. This table also explains correlation between the deterioration rate, mechanism and the exposure severity. As it can be seen in the table, the fast failure mechanism can increase the severity by two times compared to the slow mechanism.

The deterioration rate can be estimated based on the relevant available engineering and structural data, expert judgments or the combination of both (TfL, 2011). Table 3-3 shows some of the deterioration rates based on the different structural characteristics.

Table 3-2 : Rate of deterioration score (TfL, 2011).

	Exposure severity			
Rate of deterioration	**Mild**	**Moderate**	**Severe**	**Very severe**
Slow (S)	5	15	30	40
Medium (M)	15	30	45	60
Fast (F)	20	45	60	80

Table 3-3: Rate of Deterioration Depending on Structure Characteristics (TfL, 2011).

Structure Type		Bridge				Culvert					Gantry				Retaining Wall			Subway			Mast
Structural Form		Arch	Beam & Slab	Slab	Truss	Arch	Pipe	Box	Portal	Slab	Truss	Beam	Cantilever Truss	Cantilever Beam	Gravity	Cantilever	Embedded	Box	Walls	U-base & Slab	N/A
Material Types	Masonry	S	N/A	N/A	N/A	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S	M	N/A	N/A	S	N/A	N/A
	Mass Concrete	S	N/A	N/A	N/A	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S	N/A	N/A	N/A	S	N/A	N/A
	Reinforced Concrete	S	M	M	N/A	S	M	M	M	M	N/A	M	N/A	M	M	M	M	M	M	M	N/A
	Prestressed Concrete (Pre-Tensioned)	N/A	S	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S	N/A	S	N/A	N/A	S	N/A	N/A	N/A	N/A
	Prestressed Concrete (Post-Tensioned)	N/A	S	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S	N/A	N/A	N/A	N/A
	Steel (regularly painted and maintained)	S	S	S	S	S	S	N/A	N/A	N/A	S	N/A	S	N/A	S	N/A	S	N/A	N/A	N/A	F
	Weathering Steel	N/A	S	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Cast Iron / Wrought Iron (regularly painted and maintained)	N/A	S	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

3.4 FAILURE MODES

Failure or damage modes can be defined as *"typical damage affecting the condition of a bridge element"* (NCHRP, 2014). Failure modes can have different causes and mechanism as explained earlier. The common failure modes can be named as below:

- Thinning
- Creep
- Sagging
- Rapture
- Cracking
- Scaling
- Fracture
- Bending
- Chipping
- Tear
- Bucking
- Decaying
- Shear
- Yielding
- Deformation
- Wear
- Spatting
- Discoloration

There are two potential failure modes categories in bridge structures: i) Brittle and ii) Ductile.

Brittle failure modes have sudden effect of the material and they can cause great deformation in the structure. This failure mode can happen with little or no warning. There are some materials which have more potential for brittle failure mode including concrete, cast iron, stone and wood/ timber (TfL, 2011).

Ductile failure mode also happens with great deformation and it can be discussed with a measure called ductility. Materials with higher ductility can be named as steel and aluminium (TfL, 2011).

Table 3-4 shows the importance of the brittle and ductile failure modes and how they can affect the relevant score. The effect of brittle failure modes can increase by 10 compared to the ductile failure mode.

Table 3-4: Potential Failure Mode Score (TfL, 2011).

Failure mode	Score
Brittle	10
Ductile	0

3.5 FAILURE TYPE

Based on the failure modes and mechanism for the bridge structures, the failure types can be categorized in three groups:

3.5.1 WEAR-OUT FAILURE

Wear-out is a physical process that can lead to a loss, deformation or change in the structure material (EN 13306, 2010).

Therefore, failures due to wear-out is called wear-out failures and it can be explained as the *"type of failure whose probability of occurrence increases with the operating time or the number of operations of the item and the associated applied stresses"* (EN 13306, 2010). Due to the nature of wear-out failures, preventive maintenance can be a helpful measure to reduce or control this type of failure (Bradley, 2016).

3.5.2 AGING FAILURE

Ageing is a physical process that consists of different modifications of the physical and/or chemical characteristics in the structure material (EN 13306, 2010).

Aging failures can be a very important concept in reliability assessment (Li, 2002). Aging failure is described as *"failures whose probability of occurrence increases with the passage of calendar time"* (EN 13306, 2010).

3.5.3 SUDDEN FAILURE

Sudden failures, as it can be expected, happen in with very short or no warning time. This type of failures could not be predicted in advance e.g. during general inspection and monitoring (EN 13306, 2010). However, in some case, it can be possible to determine the associated risk by historical data, expert judgment and developing the distribution modeling and risk assessment (Rogovenko & Zaitseva, 2017).

PART 3 – CASE STUDY

CHAPTER 4 – CASE STUDY

4 CASE STUDY

This chapter describes the data collected from BRUTUS, the data base of Norwegian Public Roads Administration (SVV). This data includes the information of the 152 bridge structures located in Trondheim municipality. The information comprises of bridge characteristics like material type, bridge design, application and age. Appendix A shows the data base collected from SVV.

Scope, objectives, limitations, assumptions and possible source of errors are presented in this section. The information is analyzed based on different perspectives.

4.1 SCOPE AND OBJECTIVES

The main objective of this chapter is to discuss and approach a case to provide a clear understanding of the concepts discussed earlier. The scope of the case study includes the concepts below:

1. The source of given data with description.
2. Discussion and review the two groups of results from different perspectives:
   - Overall results
   - Results for the bridges with poor and very poor status

4.2 CASE STUDY LIMITATIONS, ASSUMPTIONS & POSSIBLE SOURCE OF ERRORS

This part is divided into three subsections. The main three subsections are:

- Case study limitations
- Assumptions
- Possible source of errors

CASE STUDY LIMITATIONS: Beside the general and literature study limitations, the case study also faced some limitations which can be explained as below.

- Lack of data: Some of the required information is not provided in the data base. E.g. data regarding the failure and deterioration mechanism cannot be found in the collected data.
- Sample size: The sample size in only limited to the bridges located in Trondheim municipality. Therefore, the accuracy and validity of the results cannot be used to estimate and develop a whole picture e.g. for Norway. A Larger sample size can provide more reliable trends, figures, distributions and analysis.
- Lack of reliable and/ or updated data: It can be possible that the data is not valid anymore. E.g. it can be updated or changed after the data collection.
- Failure modes and effects can be difficult to identify specifically because they affect each other and one effect can be a failure mode later on. And, the failure modes are limited. This issue has been explained more in section 4.4.2.2.
- Detailed description regarding all the subcomponents characteristics was not available in the BRUTUS database.

ASSUMPTIONS: The assumption in this case study can be listed as below.

- Even though material types can be a very detailed concept, in this project the material types are explained generally and it includes only the basic materials. It is worth mentioning that it can be possible that different elements or group of elements in a bridge structure are made of different materials. This issue has been neglected in this project.
- The risk value data is assumed to be the same for different bridge parts, structures and groups. I.e. the importance level of the elements is not included in the data and the risk values are considered for the whole bridge structure as a system.
- It is assumed that the data is reliable and it is documented, recorded and collected in suitable and acceptable conditions.
- It is assumed that human error in data registration, collection and analysis is negligible.
- The condition degree and consequence levels are assumed to be disregarded in the calculations for condition indicators.

- There are some assumptions as tables which are explained in title 4.3.2 Meta data (Data description).
- In section 4.4.2.2., the subcomponent "H19- other equipment e.g. security fence or electrical Installations" have been disregarded for the failure profile analysis for the uniform Box or tubular culvert bridges with poor and very poor condition status.
- In section 4.4.2.2., the effects of common cause failures are assumed negligible and the failures do not affect each other.
- It is assumed that the bridge users including all the traffic vehicles, people (pedestrians, cyclists, drivers etc.) and animals who use the bridge can be affected by any failure in the bridge structures.

POSSIBLE SOURCE OF ERRORS: The possible source of errors can be categorized as:

- Human errors: It can be possible to have human error in different stage of this research work e.g. in data registration, documentations, collection and analysis
- Organization errors: It can be possible to have some error in the organization (e.g. SVV in this project) which provides the data. For instance, organization errors can include some procedures and rules which may also have negative effects on this research.
- Device and sensors errors: Different types of error in the devices and sensors used in different stage of the research should be considered.
- System errors: Errors in the network systems which transfer and save the information may lead to faults in different stages of the process.

4.3 DATA

Data is described in two sections, i) Source of data, and ii) metadata (Data description).

4.3.1 SOURCE OF DATA

The data for this case study is collected from BRUTUS which is the main data base of Norwegian Public Roads Administration (SVV). This data includes the information of the 152 bridge structures in Trondheim municipality. The information compromises of the bridge characteristics e.g. material type, bridge design, application and age. Appendix A includes the whole data sheet provided for this case study. Two samples of data are shown in table 4-1. In appendix, the whole data collected from SVV is provided.

Table 4-1: Two samples of the given data by SVV.

Code	Name	App.	Form / Design	Material	Constr. year	Length	Climate zone	Accessibility	The worst damage degree	Road type	Usage load
16-1239	Støre Driftsveg	Motor way	Simply Supported	Insitu Reinf. Concrete	1988	40.4	Inland	Full access to all parts.	4 T	B	Bk 10/50
16-0987	Kroppøyen	Cycle/ Pedest-rian	Simply Supported	Steel	1979	14	Inland	N/D	6 V	N/D	N/D

4.3.2 METADATA (DATA DESCRIPTION)

Besides the provided data, it can be required to add some more descriptions regarding some of the elements in the data base. The metadata provided for each element can be explained as below:

MATERIAL: There are four materials which are mostly used in the bridge structure in Trondheim municipality.

- Insitu Reinforced Concrete
- Insitu Prestressed Concrete
- Brick/ Masonry/ Stone
- Steel

Different material type can have different failure or deterioration. Table 4-2 shows the relevant bridge failures based on the material used in a bridge structure. Based on this, it can be inferred what failure are most likely to be observed based on the material.

Table 4-2: Relevant bridge failures based on the material

Material	Failure
Concrete, timber and masonry	Brittle Failure.
Steel	Ductile Failure.
Others	Other / Not Known.

AGE: In the given data, only the data regarding the construction year is provided for each bridge. The age of the bridge can be calculated based on the equation below. It is assumed that the current year is 2019 in this calculation.

$$\text{Age of the structure} = \text{Current year (2019)} - \text{Construction year of the bridge} \tag{4-1}$$

STRUCTURE FORMS: Due to the fact that the data is provided originally in the Norwegian language, it can be required to categorize them based on some general categories in English based on (IAN 171/12, 2012). Table 4-3 shows the relevant bridge form categories in English equivalent of the forms in Norwegian.

Table 4-3: relevant bridge form categories based in (IAN 171/12, 2012).

Bridge form (in Norwegian)	Bridge form (in English)
Rør i fylling Tunnelportal Kulvert	Uniform Box or Tubular Culvert
Kassebru Sprengverksbru	Framed Span Bridges
Platebru	Slab Flat
Bjelkebru	Simply Supported
Hvelvbru	Arched
Miljøtunnel Klaffebru Svingbru Rullebru	Not Known / Other

ENVIRONMENT AND CLIMATE ZONE: As it can be seen in figure 4-1, the bridges in Trondheim are located in different climate zones. This figure is provided based on the GPS information given by SVV. The climate zone data are provided in 4 main categories as below. Figure 4-2 shows the climate zone on the map of Norway.

- Inland (the green area in figure 4-2)
- Inner coastline (the dark green area in figure 4-2).
- Coastal areas (the blue area in figure 4-2)
- Heavy Coasts (red area on the island in figure 4-2).

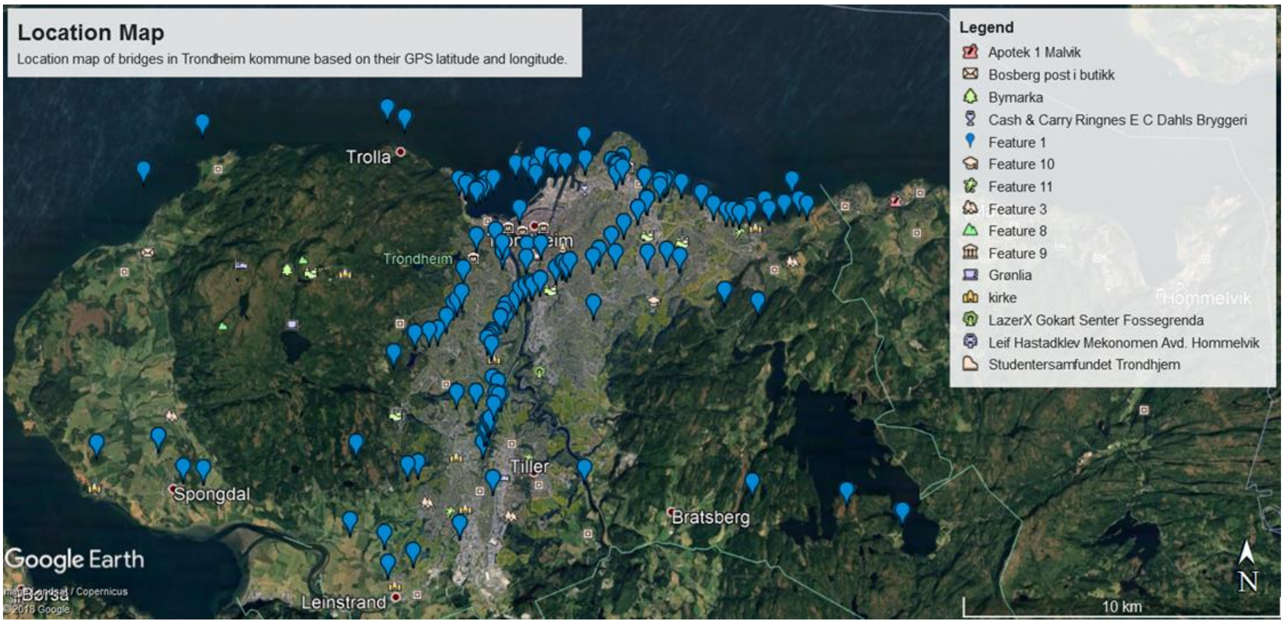

Figure 4-1: The locations of the bridges in Trondheim based on the GPS information provided.

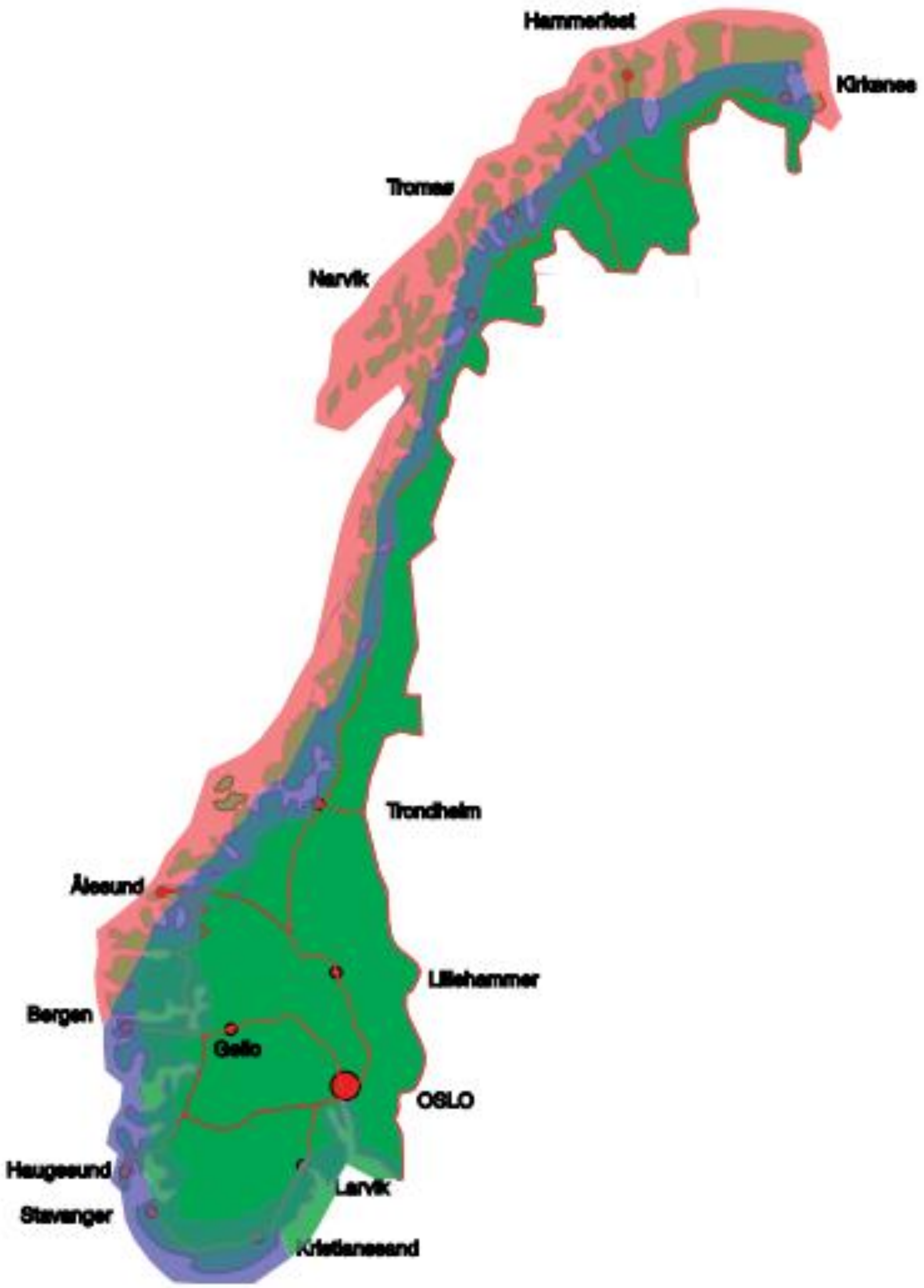

Figure 4-2: Climate zone on the map of Norway (Håndbok V440 - Bruregistrering, 2014)

The data regarding the climate zone can interpret information about the different external environmental factors including:

- Exposure to deicing salts: Table 4-4 shows how the data regarding the climate zone can be interpreted for the exposure to de-icing salts.

Table 4-4: Relation between climate zone and exposure to de-icing salts (IAN 171/12, 2012).

Climate zone	Exposure to deicing salts
Inland / Inner coastline	Moderate (Routes with de-icing salts)
Coastal areas / Heavy Coasts	Severe (Marine Environment)

- Scour risk: Table 4-5 explains how the climate zone data can give the information regarding the scour risk for a bridge structure.

Table 4-5: Relation between climate zone and scour risk (IAN 171/12, 2012).

Climate zone	Scour risk
Inland	No Risk (structure not near or adjacent to waterway)
Inner coastline	Very low risk of scour damage.
Coastal / Heavy Coasts	Scour Susceptible.
N/D (Not defined)	Not Known

- Exposure to salt water: Climate zone can also estimate the salt water exposure for the relevant structures.

    - Inland is used for areas without salt water exposure
    - Inner coastal areas are used for saltwater-exposed areas in southwestern Norway and in southern Norway that are well protected, for example, at the Oslo Fjord and in inner fjords in the western country.
    - Coastal areas are used for weathered coastal areas with some shielding in the landscape, e.g. Coastline in southwestern and southern part.
    - Heavy coastline is used only for places with extreme coastal weather conditions, for example, outer coastal areas in northern Norway and north western Norway.

- Flooding risk: Table 4-6 explains how the climate zone data can indicate the flooding risk for a bridge structure.

Table 4-6: Relation between climate zone and flooding risk (IAN 171/12, 2012).

Klimasone	Flooding risk
Innland	No Risk (structure is not near or adjacent to waterway).
Inner coastline	Low Risk (structure is adjacent to / over waterway with low likelihood of flood damage).
Coastal areas / Heavy Coasts	Moderate / High Risk (structure is adjacent to / over waterway with medium / high likelihood of flood damage)
N/D	Not Known

INSPECTION ASSESSMENT: There some accessibility methods which are provided in the data from SVV. The accessibility methods can be named as bridge lift, climbing equipment, boat, scissor lift and others. Table 4-7 tabulates the accessibility methods and what it indicates regarding the bridge inspection assessment.

Table 4-7: Indication of the Inspection assessment data.

Level of visual accessibility during a general Inspection	Inspection assessment
No need.	Full access to all parts of the structure.
No need and use of 1 method.	All parts of the structure visible from a distance (including the use of binoculars).
Only one method is used. / Use of 2 or more methods.	Limited Access / View of Structure.
N/D	Not Known / Other.

PRIORITY INDICATORS: The priority indicators is referred as worst damage degree in the data. It is noteworthy that the same bridge structure might have experienced more than one priority grade. However, the worst damage degree is the worst priority grade that a bridge structure has ever experienced. The priority grade can be calculated by equation 4-2 (Håndbok V440 - Bruregistrering, 2014) and using table 4-8.

$$\text{Priority P} = \text{Condition degree} * \text{Consequence level} * \text{Consequence type} \qquad (4\text{-}2)$$

Table 4-8: Risk matrix to indicate the priority value (Håndbok V440 - Bruregistrering, 2014).

Consequence level	**4**	**4**	**8**	**12**	**16**
	3	**3**	**6**	**9**	**12**
	2	**2**	**4**	**6**	**8**
	1	**1**	**2**	**3**	**4**
Priority		**1**	**2**	**3**	**4**
		Condition degree			

Table 4-9 shows the interpretation of each color in the risk matrix.

Table 4-9: Colour descriptions of the risk matrix for table 4-8 (Håndbok V440 - Bruregistrering, 2014).

Color indications	**Description**
Red zone	Actions or assessment of necessary measures immediately or within 1 year.
Yellow zone	Actions or evaluation of necessary measures.
Green zone	Development is followed up on the next inspection.

The worst damage degree can provide two types of information:

i. Consequence type
ii. Risk values or condition performance indicators.

Based on table 4-1, the worst damage degree (or highest priority grade) is given as a combination of numbers and one alphabet e.g. 6V. The letter indicates the consequence type and the number shows the risk value or condition performance indicators.

Note that a bridge can have many priority values however the highest of which are chosen as the worst damage degree and it is only one for each bridge. Table 4-10 explains the defined consequence types in the data and table 4-11 describes how the worst damage degree can be used to define the condition performance indicators. For instance, the bridge with the worst damage degree of 6V is with the poor condition performance that results in increased maintenance cost.

Table 4-10: Consequence type description (Håndbok V440 - Bruregistrering, 2014).

Consequence type	Explanation
B	Carrying capacity
T	Road safety
V	Increased maintenance costs
M	Environmental / Aesthetics

Table 4-11: Interpretations of the worst damage degree for bridge condition indicator.

Zone colour	Worst damage degree	Condition Performance Indicator (Average score)
Red zone	12 or 16	Very poor
Yellow zone	8 or 9	poor
	6	
Green zone	3 or 4	Good
	1 or 2	
N/D	---	Not Known / Other.

APPLICATION AND LOAD TYPE: There are two types of the bridge groups which are identified in the provided data. In table 4-12, it can be seen how the bridge groups are described.

Table 4-12: Bridge groups descriptions (IAN 171/12, 2012).

Bridge group	Description
A	Full Highway Loading + Heavy Load Route.
B	Full Highway Loading.
N/D	Other / Not known.

4.4 RESULTS

4.4.1 OVERALL RESULTS

Based on the data collected from SVV, some inferences can be presented. These results show different perspectives of the information for the bridge structures in Trondheim municipality. The results are categorized based on the specific bridge characteristics information.

MATERIAL: Table 4-13 shows the bridge data in Trondheim municipality based on the material used. The pie chart in figure 4-3 illustrates the percentage values of the material used. As it can be seen in figure 4-13, most of the bridges in Trondheim are made of Insitu (reinforced / prestressed) concrete. Therefore, based on table 4-2, in Trondheim the brittle failure can be considered as the important concerns compared to the ductile failure in steel structures. Based on this result, it can be recommended that the brittle failure in Insitu (reinforced / prestressed) concrete can be analyzed and take more into consideration in the operation, inspection and maintenance planning.

Table 4-13: Bridge data based on the material used.

Material Type	No. of bridges	Percentage value (%)
Steel	20	**13**
Insitu Reinforced Concrete	118	**78**
Insitu Prestressed Concrete	10	**7**
Brick/ Masonry/ Stone	2	**1**
N/D (Not defined)	2	**1**
Sum	152	100

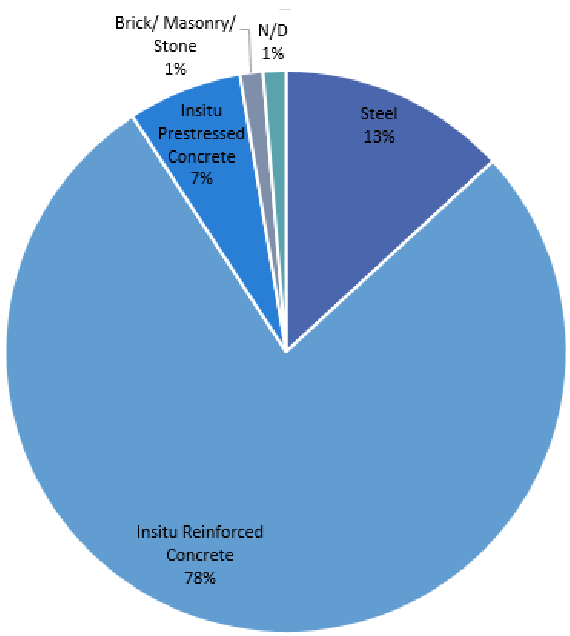

Figure 4-3: Pie chart for the bridges in Trondheim based on the material used.

AGE: Table 4-14 shows the bridge data based on the construction years. Construction years are divided into 5 intervals of 21 years based on the lowest (1912) and highest (2017) construction year provided in the data.

Figure 4-4 and 4-5 illustrates that there are more bridges built in recent decades compared to before. However, there is a fall for the last construction interval, the figure shows that most of the bridges are built from approximately 1954 to 2017. As it is explained earlier, the failure possibility and deterioration rates can increase with age and this can be a point that can be considered in bridges in Trondheim municipality.

Table 4-14: Bridge data based on the construction intervals.

Construction intervals (year)	No. of bridges	Percentage value (%)
1912-1932	2	**1**
1933-1953	7	**5**
1954-1974	18	**12**
1975-1995	69	**45**
1996-2017	56	**37**
Sum	152	100

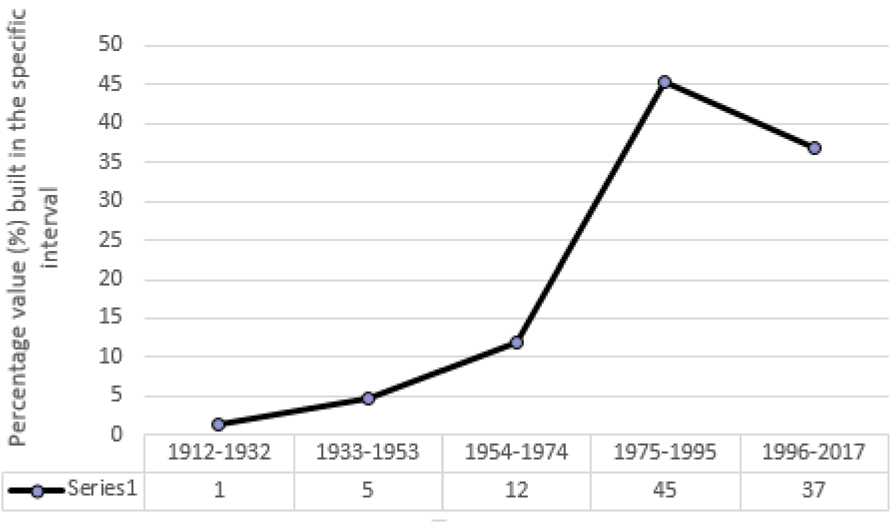

Figure 4-4: Percentage values of the brigde built in a specific contruction interval.

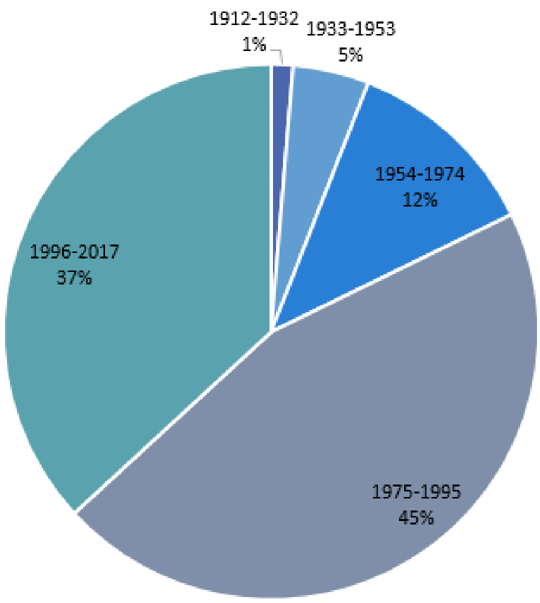

Figure 4-5: Pie chart for the bridges in Trondheim based on the construction intervals.

ENVIRONMENT AND CLIMATE ZONE: Based on the provided data regarding the climate zones, the bridge data are calculated in table 4-15. Figure 4-6 also shows the percentage values of this data. As it can be seen in the table and the figure, most of the bridges in Trondheim are located in the inland areas. It can be helpful to interpret some estimations regarding the external environmental factors for the bridges. These estimations are explained in the following.

Table 4-15: Bridge data based on the climate zone.

Climate zone	No. of bridges	Percentage value (%)
Inland	136	**89**
Inner coastline	7	**5**
Coastal areas	4	**3**
Heavy Coasts	0	**0**
N/D (Not defined)	5	**3**
Sum	152	100

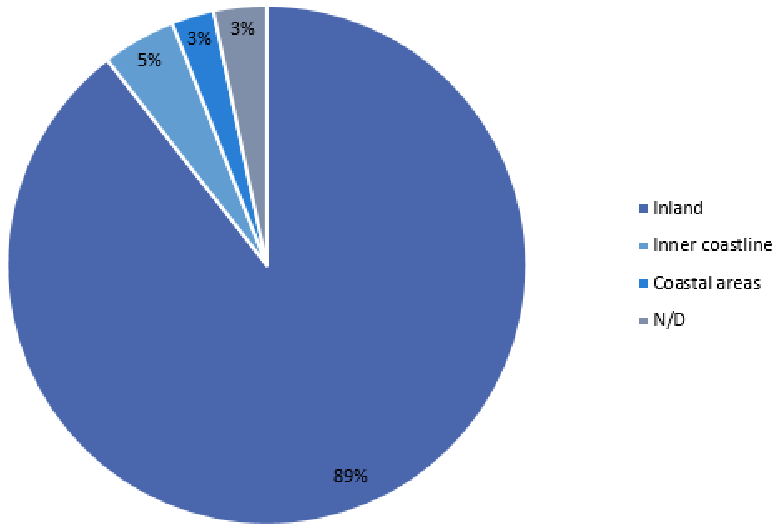

Figure 4-6: Pie chart for the bridges in Trondheim based on the climate zone.

- Exposure to deicing salts: Based on table 4-4, it can be estimated that the routes exposure to the deicing salts can be moderate because most of the bridges are located in the inland and inner coastline.

- Scour risk: Based on table 4-5, it can be expected that the bridges in Trondheim has no risk or very low risk of scour damage. The reason for this estimation is that most of the bridge structures are not near or adjacent to waterway.

- Exposure to salt water: As it is already explained, the salt-water exposure can be almost zero for the inland structure which are the majority of the bridge structures in Trondheim.

- Flooding risk: Because of the same reason as the other three points and table 4-6, there are no risk or very low risk of flooding for the bridge structures in Trondheim. Because structures are not near or adjacent to waterway, or they are adjacent to / over waterway with low likelihood of flood damage).

APPLICATION AND LOAD TYPE: Table 4-16 and figure 4-7 show the application and load type for the bridge structures located in Trondheim. As it can be seen, the majority of the bridges are from type A (84%). Therefore, according to table 4-12 and shown in figure 4-10, most of the bridges can be considered as the full highway loading with heavy load routes. Also, as mentioned in chapter 3, heavy loading can increase the failure and deterioration in the bridge structures.

Table 4-16: Bridge data based on the application and load type.

Application and load type	No. of bridges	Percentage value (%)
A	127	**84**
B	2	**15**
N/D (Not defined)	23	**1**
Sum	152	100

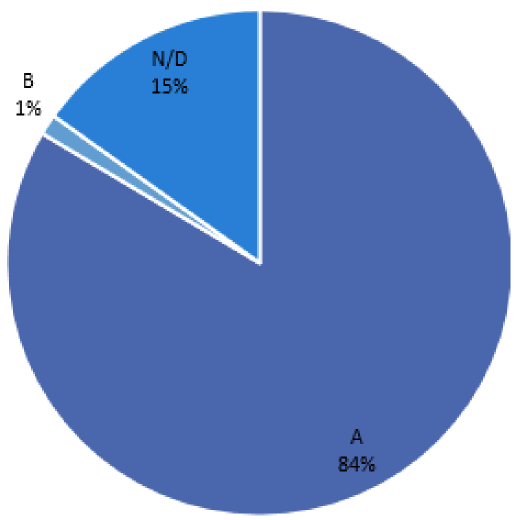

Figure 4-7: Pie chart for the bridges in Trondheim based on the application and load type.

PRIORITY INDICATORS: Priority indicators are discussed regarding the consequence type and the risk values provided for the worst damage degree for the bridges.

- Consequence type: As it can be seen based on table 4-17 and figure 4-8, majority of the consequence types is related to road safety and increased maintenance costs.

Table 4-17: Bridge data based on the consequence type.

Abbreviation	Description of consequence type	No. of bridges	Percentage value (%)
B	Carrying capacity	12	8
T	Road safety	69	45
V	Increased maintenance costs	62	41
M	Environmental or Aesthetics	5	3
N/D	Not defined	4	3
	Sum	152	100

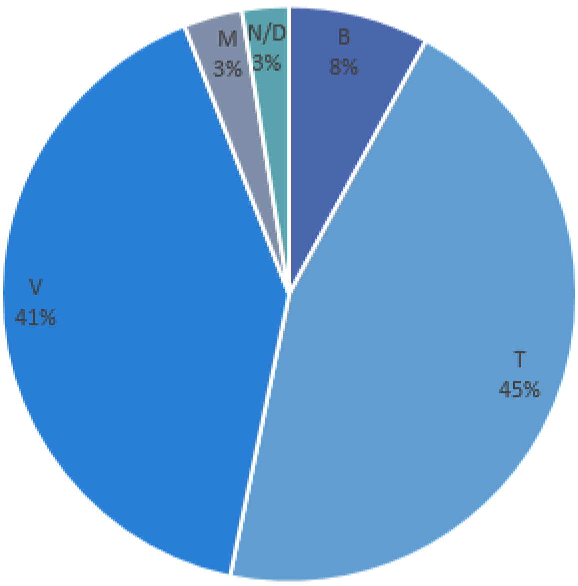

Figure 4-8: Pie chart for the bridges in Trondheim based on the consequence type.

➢ Risk values: As noticed in table 4-18 and figure 4-9, almost more than half of the bridges have good condition performance indicators and the other half of the bridges have poor and very poor.

Table 4-18: Bridge data based on risk values.

Risk zone	**Condition Performance Indicator**	**No. of bridges**	**Percentage value (%)**
Red zone	Very Poor	14	**9**
Yellow zone	Poor	49	**32**
Green zone	Good	83	**55**
N/D (Not defined)	-	6	**4**
Sum		152	100

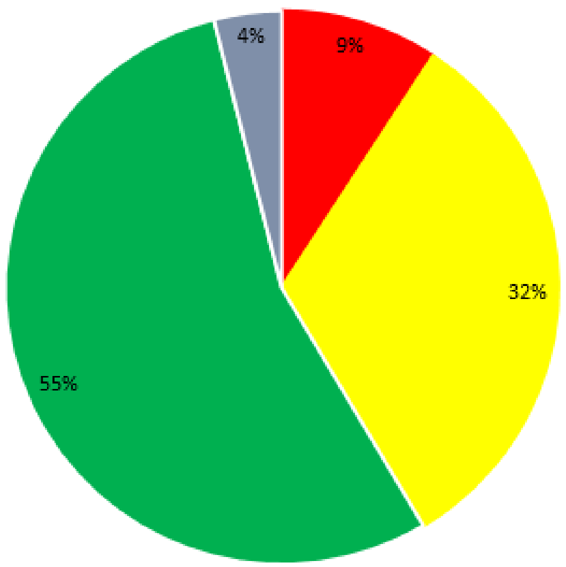

Figure 4-9: Pie chart for the bridges in Trondheim based on the risk values.

4.4.2 RESULTS FOR THE BRIDGES WITH POOR AND VERY POOR CONDITION PERFORMANCE INDICATORS

As it has been shown earlier in the overall results, most of the bridges in Trondheim municipality have good condition performance indicators. Therefore, the bridges with poor and very poor condition performance indicators have been chosen for further detailed study in this section. This study can be helpful in order to improve the condition of these bridges and hence to be able to achieve good condition as the rest of 55% of the bridges with the good condition performance indicators. These bridges are discussed from 2 perspectives as listed below:

1. Consequence types
2. Bridge structure forms

4.4.2.1 CONSEQUENCE TYPES

In order to indicate the consequence types for the bridges with poor and very poor condition performance indicators, results based on the data is tabulated in table 4-19. Based on table 4-19 and Figure 4-10, traffic safety is the most important consequence type. This is followed by carrying capacity and increased maintenance costs. Consequence types relating to environmental or aesthetics is approximately 2% and hence it can be considered almost negligible.

Table 4-19: Percentage indication of consequence type in red and yellow zone

Abbreviation	Description of consequence type	Red zone (%)	Yellow zone (%)	Both yellow & red zone
B	Carrying capacity	21	12	14
T	Road safety	64	55	57
V	Increased maintenance costs	14	31	27
M	Environmental or Aesthetics	0	2	2

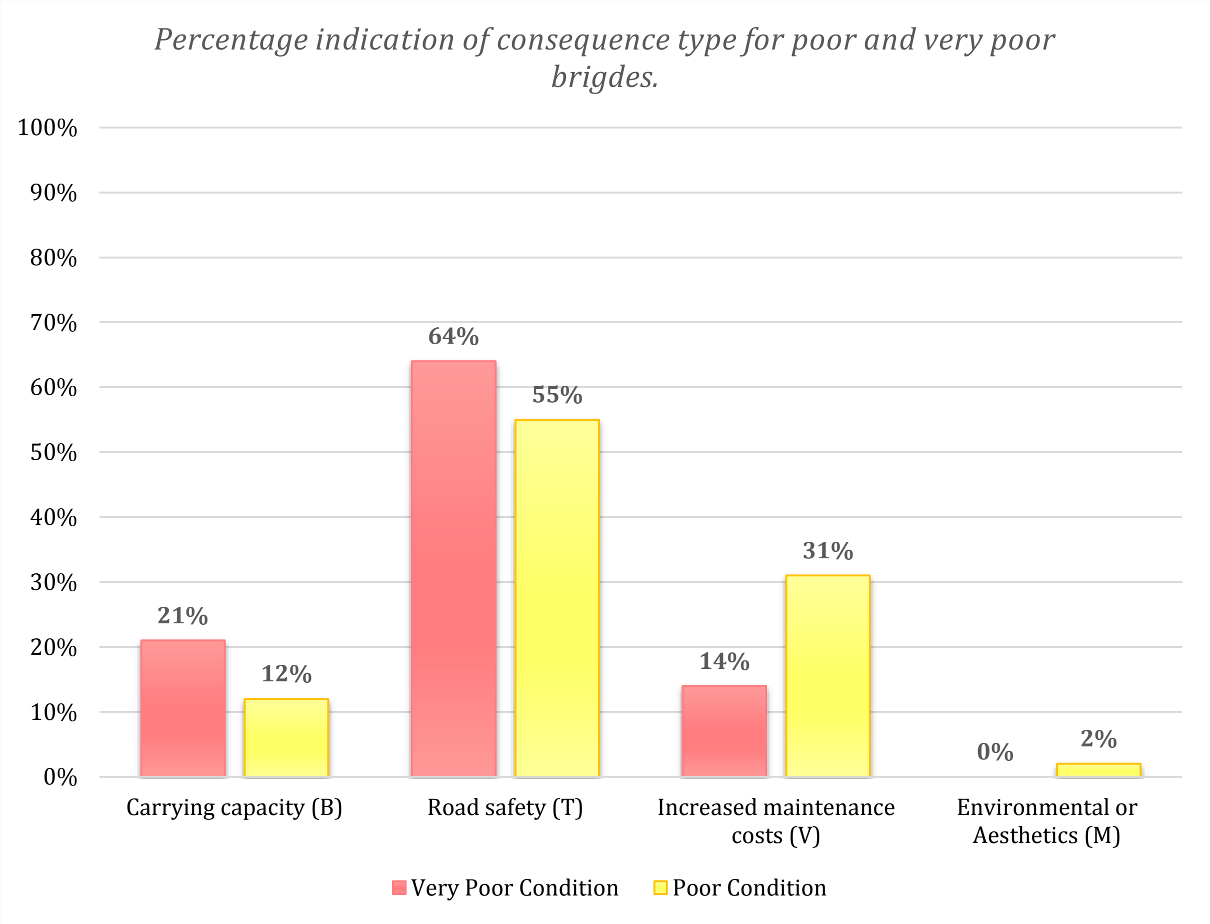

Figure 4-10: Percentage indication of consequence type in red and yellow zone in bar chart.

4.4.2.2 BRIDGE STRUCTURE FORMS

Bridges with poor and very poor condition performance indicators have also been discussed based on the bridge structure forms. Based on table 4-20, the most common bridge structure forms in red and yellow zone can be considered as:

- Uniform box or tubular culvert (30%)
- Simply supported (29%)
- Slab flat (27%).

Uniform box or tubular culvert and simply supported bridges have been selected for further studies. Note that framed span and slab flat bridges have very similar structures so they can be considered in the same group.

Table 4-20: Percentage indication of consequence type in red and yellow zone

Bridge form (in Norwegian)	Bridge form (in English)	No. of bridges	Percentage value (%)
Rør i fylling Tunnelportal Kulvert	Uniform Box or Tubular Culvert	19	30
Kassebru Sprengverksbru	Framed Span Bridges	2	3
Platebru	Slab Flat	17	27
Bjelkebru	Simply Supported	18	29
Hvelvbru	Arched	2	3
Miljøtunnel Klaffebru Svingbru Rullebru	Not Known / Other	5	8
TOTAL		63	100

4.4.2.3 SUBCOMPONENTS FOR UNIFORM BOX/ TUBULAR CULVERT AND SIMPLY SUPPORTED STRUCTURES

Based on the SVV database, BRUTUS, main components and subcomponents for all the bridges with uniform box/ tubular culvert and simply supported structures with poor and very poor condition performance are listed in table 4-21 and 4-22. Based on BRUTUS, there are 10 main units or components in the bridges however the subcomponents can be different based on the structural forms. The 10 main systems can be explained below:

- A: Shared Cost
- B: Ground
- *C: Substructure
- *D: Superstructure
- E: Deck / wear layer
- F: Construction in filling / foundation
- G: Supporting structure
- *H: Equipment
- *I: Special quay equipment
- J: Special installation

System A is not relevant in this project as it is used in the tender documents or contracts (Håndbok V440 - Bruregistrering, 2014).

The units with the code B, E, F, G, J are registered with up to 1-digit level (in addition to the letter code) and used for unit types which do not have significant impact on the static system of the structure (Håndbok V440 - Bruregistrering, 2014). The units C, D, H, I are marked with one star in the following tables and are registered with up to 2 digit levels in addition to the letter code (Håndbok V440 - Bruregistrering, 2014). 2-digit codes in addition to the letter code indicates the highest level of detail / degree of information in the item code (Håndbok V440 - Bruregistrering, 2014).

Table 4-21 and 4-22 show the list of main components and subcomponents in the uniform box or tubular culvert and simply supported bridge structures respectively. The codes mentioned in the tables are based on the SVV database, BRUTUS.

Table 4-21: Subcomponents for uniform box or tubular culvert bridges based on BRUTUS database.

Unit/ Component	Code	Subcomponent
A: Shared Cost	**-**	-
B : Ground	**B4**	Filling
	B7	Slope protection under abutments concrete stones
	B9	Hot-dip trapping grate in front of inlet
***C: Substructure**	**C1**	Abutments
	C2	Pillar
***D: Superstructure**	**D1**	Plate/Sheet - main bearing
	D22	Cross member
E: Deck / wear layer	**E1**	Bridge deck - carrying system
	E2	Wear layer/ moisture insulation
	E3	Edge beam
	E5	Wear layer in culvert
F: Construction in filling / foundation	**F1**	Foundation/ base plate
	F2	Walls
	F3	Roof
	F5	Tubular / pipe elements
	F7	Wings
	F8	Load distribution plate
	F9	Other constructions
G: Supporting structure	**G2**	Walls - support wall downside
	G7	Kjeglemur - Internal walls
***H: Equipment**	**H13**	Seal/ joints construction (not for waterproofing)
	H15	Railing
	H16	Water drain - Pumping station or drainage system
	H17	Cables
	H19	others e.g. security fence or el. Installation
	H21	Lights
	H24	Noise barrier
	H26	Hatch / door
	H29	Marking signs
	H32	Staircase
***I: Special quay equipment**	**-**	-
J: Special installation	**J1**	Drainage system
	J2	Ventilation systems

Table 4-22: Subcomponents for simply supported bridges based on BRUTUS database.

Unit/ Component	Code	Subcomponent
A: Shared Cost	**-**	**-**
B : Ground	**B2**	Piles e.g. of concrete
	B4	Filling
	B6	Erosion control
	B7	Slope protection under abutments concrete stones
	B9	Riverbed
***C: Substructure**	**C1**	Abutments
	C2	Pillar
	C3	Tower/ tower house
	C6	Motvekthus (counterweight house)
***D: Superstructure**	**D1**	Plate/Sheet -main bearing/ carrying system
	D2	Beams
	D21	Main beams
	D22	Cross member
	D3	Kasse
	D9	Other superstructures e.g. pavements
	D71	Main beams
	D72	Cross member
	D73	Counter balance
	D74	Toothed gear - powertrain
	D76	Balancing system
	D77	Machine - power supply unit
E: Deck / wear layer	**E1**	Bridge deck - carrying system
	E2	Wear layer/ moisture insulation
	E3	Edge beam
F: Construction in filling / foundation	**F7**	Wings
	F8	Load distribution plate
G: Supporting structure	**G2**	Walls - support wall downside
***H: Equipment**	**H11**	Storage/stock
	H13	Seal/ joints construction (not for waterproofing)
	H14	Joint threshold
	H15	Railing
	H16	Water drain - Pumping station or drainage system
	H17	Cables e.g. for hot-dip trapping
	H19	others e.g. security fence or el. Installation
	H21	Lights
	H26	Hatch / door
	H27	Utsmykning (embellishment)
	H29	Marking signs e.g. made of aluminum

Unit/ Component	Code	Subcomponent
*H: Equipment	H31	Ladder
	H32	Staircase
	H39	Other fixed access equipment
	H41	Machine house
	H44	Control tower
	H51	Instrumentation/ gauges in the control room.
*I: Special quay equipment	I11	Containment boom
J: Special installation	J9	Other special installation e.g. fuse box

4.4.2.4 FAILURE MODE AND EFFECTS ANALYSIS (FMEA) FOR UNIFORM BOX/TUBULAR CULVERT

In this section, the uniform box or tubular culvert bridges (the most common structure forms for bridges with poor and very poor condition performance indicators) are discussed more regarding the failure profile.

Failure Mode and Effects Analysis (FMEA) has been chosen as the methodology to discuss the failure profile in more detail. FMEA can be helpful to achieve a better and more clear understanding regarding the specific structure and to minimize the associated risks (Stamatis, 2003). It can be used as the first step in studying the failure profile and improving the reliability, safety and quality before more detailed analysis of the structure (Stamatis, 2003).

As explained earlier, the elements with the code B, E, F, G, J are used for element types which do not have significant impact on the static system of the structure (Håndbok V440 - Bruregistrering, 2014). Therefore, the elements with codes C, D, H, I are selected for uniform box or tubular culvert bridge structure for further studious. Note that there is no element code I registered in BRUTUS for this form of bridge.

Table 4-21 presents the failure modes, causes, mechanism and effects, FMEA, for each influencing components and subcomponents (C, D and H) for uniform box/tubular culvert bridges. This table is based on the information collected from literature studies. As inferred from the table, the failure modes and effects can be challenging to identify specifically because they affect each other. I.e. a failure mode for one subcomponent can lead to an effect and therefore a failure mode for another subcomponent.

Figure 4-11 shows this continuous interaction between failure modes and failure effects. Thus, the failure modes are mostly limited to the list below.

- Thinning
- Creep
- Sagging
- Rupture
- Cracking
- Scaling
- Fracture
- Bending
- Chipping
- Tear
- Buckling
- Decaying
- Shear
- Yielding
- Deformation
- Wear
- Spalling
- Discoloration

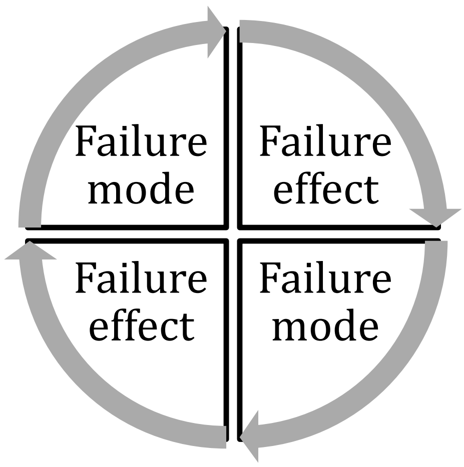

Figure 4-11: Continuous interaction between failure modes and failure effects.

Table 4-23: FMEA for uniform box/tubular culvert.

Unit/ Comp-onent	Code	Sub-component	Item function	Failure modes	Failure causes	Failure mechanism	Failure effects		
							Local	System	External
*C: Substructure	C1	Abutments	Stabilize the structure against the ground on both ends	Thinning	-Ice Formation on the surfaces -Corrosion -Deicing material	-Freeze thaw cycle both on the structure and from the ground. -Chloride/ sulphate attack.	Instable abutments	Instability in the bridge structure, which can result in collapse.	Bridge collapse can result in damage to the animals, property, vehicles or bridge users.
				Rupture	-Mishandling -Maintenance activities -Traffic accident -Waves	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
				Fracture	-Mishandling -Maintenance activities -Traffic accident -Waves	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
	C2	Pillar	Stabilize the bridge above the ground (in the middle)	Wear	Age of structure	Abrasion			
				Bending	-Excessive pressure /loads. -Mishandling -Maintenance activities -Traffic accident -Scouring	Too high applied pressure	Instable pillars	Instability in the bridge structure, which can result in collapse.	Bridge collapse can result in damage to the animals, property, vehicles or bridge users.
				Cracking	-Mishandling -Maintenance activities -Traffic accident -Scouring	Contact with hazardous physical or chemical factors			
				Discoloration	Salt deposits in water	Efflorescence			
				Creep	-Age of structure -Climate conditions	-Abrasion -Erosion -Fatigue			

*D: Superstructure	**D1**	Plate/Sheet - main bearing	Minimize and control the stresses in and to the structure	Thinning	-Freeze thaw cycle both on the structure and from the ground -Corrosion -Deicing material	-Freeze thaw cycle both on the structure and from the ground. -Chloride/ sulphate attack.	Fragile plate or sheets that cannot distribute and control the applied stressed through the structure.	Excessive stress on the bridge structure, which can result in collapse.	Bridge collapse can result in damage to the animals, property, vehicles or bridge users.
				Rupture	-Mishandling -Maintenance activities Traffic accident -Waves	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
				Fracture	-Mishandling -Maintenance activities Traffic accident -Waves	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
	D22	Cross member	Distribute the applied loads in and to the structure	Wear	Age of structures	Abrasion	Instable cross members that cannot distribute and control the applied loads through the structure.	Excessive loads on the bridge structure which can result in collapse.	Bridge collapse can result in damage to the animals, property, vehicles or bridge users.
				Bending	-Excessive pressure /loads. -Mishandling -Maintenance activities -Traffic accident -Scouring	Too high applied pressure			
				Cracking	-Mishandling -Maintenance activities Traffic accident -Scouring	Contact with hazardous physical or chemical factors			
				Discoloration	Salt deposits in water	Efflorescence			
				Creep	-Age of structure -Climate conditions	-Abrasion -Erosion -Fatigue			

***H: Equipment**	**H13**	Seal/ joints construction	Protect the structure edges from applied loads.	Same as unit D and C (based on the characteristics).	Same as unit D and C (based on the characteristics).	Same as unit D and C (based on the characteristics).	The load is not controlled in structure edges.	Instable joints can lead to collision.	Potential damage to the animals, property, vehicles or bridge users.
	H15	Railing	-Control the traffic flow. -Protect other bridge users.	Bending	-Excessive pressure /loads. -Mishandling -Maintenance activities -Traffic accident	Too high applied pressure.	No protection in traffic flow and for the bridge users which can result in fatal accidents.	Traffic accidents can lead to failure of critical bridge elements and collision.	
				Fracture	-Mishandling -Maintenance activities Traffic accident	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
	H16	Water drain (Pumping station/ drainage system)	Lead the water away from the structure	Clogged inlet or outlet	-Lack of maintenance and cleaning. -Ice formation on the inlet and outlet.	-Ice impact in case of ice formation on the inlet and outlet.	Water flow can be stuck in the drainage.	-Water flow can be led to the structure. -Potential damage to the structure (e.g. corrosion).	Damage to the critical bridge elements can lead to collapse.
	H17	Cables	Support bridge structure	Sagging	-Mishandling -Maintenance activities -Excessive ice formation -Wind -Traffic accident	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc. -Ice impact in case of ice formation.	Failure in bridge support.	Instability in the bridge system.	Potential damage to the animals, property, vehicles or bridge users.
				Ruptured	-Excessive applied load -Excessive Ice formation				
	H21	Lights	Provide better vision for the traffic and the bridge users	Sagging	-Mishandling -Maintenance activities -Excessive ice formation -Wind -Traffic accident	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc. -Ice impact in case of ice formation.	Lack of sufficient light.	Lack of proper vision for the traffic and bridge users.	fatal accidents and damages to the animals, property, vehicles.
				Stop functioning	-Mishandling -Improper maintenance activities				

*H: Equipment	**H24**	Noise barrier	Control the noise pollution	Failed to reduce the noise level	-Age of structure -Excessive ice formation -Improper maintenance	-Ice Impact. -Fatigue.	Lack of noise protection.	Discomfort for the bridge users.	Discomfort in the area.
	H26	Hatch / door	Separate different areas	Creep	-Age of structure -Climate conditions	-Abrasion -Erosion -Fatigue	Lack of separation units.	Possibility of misusing the area.	Discomfort for the bridge users.
				Cracking	-Mishandling -Maintenance activities Traffic accident -Scouring	-Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			
	H29	Marking signs	Provide relevant traffic information for the bridge users	Sagging	-Mishandling -Maintenance activities -Excessive ice formation -Wind -Traffic accident	-Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc. -Ice impact in case of ice formation.	Lack of proper and required signs.	-Lack of traffic information for the traffic and the bridge user. -Separated signs can damage the bridge users.	Lack of traffic information can results in fatal accidents and damages to the animals, property, vehicles.
				Discoloration	- Salt deposits in water -Vandalism	-Salt deposits due to efflorescence			
				Bending	-Excessive pressure /loads. -Mishandling -Maintenance activities -Traffic accident -Scouring	Too high applied pressure			
	H32	Staircase	Accessibility to two sides of the road	Creep	-Age of structure -Climate conditions	-Abrasion -Erosion -Fatigue	Lack of proper accessibility through the bridge.	Potential hazardous situations that can result in harm and injury for the bridge users.	Discomfort for the bridge users.
				Cracking	-Mishandling -Maintenance activities Traffic accident -Scouring	Collision with the objects (relevant to failure causes) e.g. vehicles, wave currents etc.			

CHAPTER 5 – DISCUSSION

5 DISCUSSION

The main objective of the case study is to discuss and approach a case to provide a clear understanding of the concepts discussed in chapter 2 and 3. In order to achieve this, the bridges in Trondheim municipality are categorized based on the characteristics and failure status. Moreover, bridges with the poor and very poor condition status in Trondheim were discussed in more detail.

The bridge characteristics were discussed based on the available data for the bridges located in Trondheim municipality. Based on the material type, most of the bridges in Trondheim are built from Insitu (reinforced /prestressed) Concrete. Therefore, brittle failure can be taken more into consideration compared to the ductile failure in steel structures.

Regarding the age and/or construction years, there is a fall in the last defined construction interval, it is shown that most of the bridges in Trondheim are built from approximately 1954 to 2017.

According to the environmental factors, except the exposure to deicing salts which is moderate, scour risk, exposure to salt water and flooding risk are classified as low risk or even there is no risk.

With respect to the load types, most of the bridges can be considered as the full highway loading with heavy load route.

Failure concepts are also discussed by a priority indicator (or worst damages degree) provided in the data. Priority indicator addresses two issues:

i) Consequence types
ii) Risk values or condition performance indicators.

Most of the consequence types are concerned with road/traffic safety and increased maintenance costs. Almost half of the bridges have good condition performance indicators (green risk area) and the other half of the bridges have poor (yellow risk area) and very poor (red risk area). Road/traffic safety is also indicated as the most important consequence type in both red and yellow zone.

Based on the overall results, the bridges with poor and very poor condition performance indicators have been chosen for further detailed study. These bridges are discussed from 2 perspectives explained as below:

1. Consequence types: Traffic safety is the most important consequence type identified for the bridges with poor and very poor condition performance. Moreover, carrying capacity and increased maintenance costs are the next important consequence types respectively. Consequence types relating to environmental or aesthetics can be considered almost negligible.
2. Bridge structure forms: The uniform box or tubular culvert bridges (30%) and simply supported (29%) structures are identified as the most common structure forms for bridges with poor and very poor condition performance indicators. The components and subcomponents for these two bridges form is presented in table 4-21 and 4-22. The most important components which have significant impact on the static system of the structure are identified for uniform box or tubular culvert bridges (the most common structure forms) according to (Håndbok V440 - Bruregistrering, 2014) and BRUTUS database. These components are selected as C (substructure), D (superstructure) and H (equipment).

   The FMEA methodology has been used for these components to find the relevant failure modes, causes, mechanism and effects. For the components C and D, failure modes can be thinning, creep, rupture, bending, cracking, fracture, wear and discoloration. However, for the component H, the failure modes can vary based on different characteristics of the subcomponents.

   Based on the component characteristics and the FMEA analysis done for these components and their subcomponents, there can be generally nine common failure modes identified. These failure modes are:

   - Thinning
   - Creep
   - Rupture
   - Bending
   - Cracking
   - Fracture
   - Wear
   - Discoloration
   - Sagging

   In case of a bridge collapse, the consequences can be fatal and it can result in damage to the animals, property, vehicles or bridge users.

PART 4 –CONCLUSION

CHAPTER 6 – CONCLUSION AND FURTHER STUDIES

6 CONCLUSION AND FURTHER STUDIES

The objective of this chapter is to provide an overall review of the whole research project and to answer the research questions mentioned in the title "1.3 RESEARCH QUESTIONS" based on the objectives. Furthermore, it includes the possible further studies in this area.

➢ **SUMMARY OF THE LITERATURE REVIEW AND THE CASE STUDY**

The summary of the literature review and case study parts are reviewed in this section. The purpose of this summary is to provide an overview through the main concepts of the project. More detailed description of each topic can be found in the relevant chapters.

Literature review: it consists of chapter 2 and 3.

Chapter 2 consists of the introduction, main objectives, limitations and description of the different bridge characteristics and elements. Various research articles were analyzed and information have been extracted from them. Chapter 7 contains the list of researches referred in this study. The objective of this chapter is to explain and clarify the relevant concepts regarding the bridge structure.

Based on the introduced bridge characteristics, the concepts in bridge reliability, lifetime performance characteristics and failure profile are described in chapter 3. Different failure causes, failure and deterioration mechanisms, failure modes and different failure types are discussed in this chapter.

Case study: The case study is described in chapter 4 including limitations, assumptions and possible source of errors. The collected data is from BRUTUS, the database of Norwegian Public Roads Administration (SVV). This data includes the information of the 152 bridge structures located in Trondheim municipality. The information compromised of bridge characteristics such as material type, bridge design, application and age.

The main objective of the case study is to discuss and approach a case to provide a clear understanding of the concepts discussed earlier. The bridges in Trondheim municipality were categorized based on the characteristics introducing in the first section and their failure status was investigated based on the matrices introduced in second section. Moreover, bridges with the poor and very poor condition status in Trondheim were discussed in more detail.

- **RESEARCH QUESTIONS**

Research questions can be listed and answered as below.

1. How bridge structures can be categorized?

The major and typical parts of a bridge can be categorized into four main groups such as: i) Superstructure, ii) Substructure, iii) Foundation, and iv) Other basic parts. Other elements like deck, beam, span and pier can be included in one of these three main parts.

Furthermore, the bridge characteristics are categorized from 10 different perspectives, as:

1. Material type
2. Age
3. Span / height / headroom / length
4. Portability
5. Structure forms (design and construction)
6. Environment
7. Inspection assessment
8. Condition indicators
9. Applications and load type
10. Route supported and obstacles crossed

The importance of each category has been explained in chapter 2. It also described how these characteristics can affect the reliability and failure profile of the bridge structures.

2. How to define reliability and failure profile concepts for the bridge structures? I.e. when does a bridge fail?

Both concepts are described relying on the physical and structural definitions for reliability and failure concepts. "*Reliability is the ability of a structure or structural member to fulfil the specified requirements, during the working life, for which it has been designed"* (ES ISO 2394, 2012) and *the termination of this ability in a structure can be defined as failure* (NCHRP, 2014). I.e. a bridge fails when there is any one of structure elements are not fully or partially functioning that can lead to a potential risk of damage or harm against human, environment and assets. The failure profile includes discussing different failure causes, failure mechanism, and their corresponding modes and types.

3. **Categorize the bridges in Trondheim municipality based on the output from question 1 and list their failure profile based on question 2.**

Based on the first question, the available characteristics for the bridges in Trondheim are listed. Some of these characteristics are discussed further in the figures and charts.

Based on the output from question 1:

The bridge characteristics are discussed based on the available data for Trondheim bridges.
Based on the material, most of the bridges in Trondheim are built from Insitu (reinforced /prestressed) Concrete. Therefore, the brittle failure can be taken more into consideration compared to the ductile failure in steel structures.

Regarding the age and/or construction years, however there is a fall in the last defined construction interval, it is shown that most of the bridges in Trondheim are built from approximately 1954 to 2017.
According to the environmental factors, except the exposure to deicing salts which is moderate, scour risk, exposure to salt water and flooding risk are low risk or even there is no risk.
Moreover, with respect to the load types, most of the bridges can be considered as the full highway loading with heavy load route.

Based on the output from question 2:

Failure concepts are discussed by a priority indicator (or worst damages degree) provided in the data. Priority value addresses two issues:

i) Consequence types and
ii) Risk values or condition performance indicators.

Most of the consequence types are concerned with road/traffic safety and increased maintenance costs. Only half of the bridges have good condition performance indicators (green risk area) and the other half of the bridges have poor (yellow risk area) and very poor (red risk area). Road/traffic safety is also indicated as the most important consequence type in both red and yellow zone.

4. **What are the main failure modes in the failure profile of the bridges with poor and very poor condition performance indicator?**

In this report, the uniform box or tubular culvert bridges is identified as the most common structure forms for bridges with poor and very poor condition performance indicator based on BRUTUS database. The most important components which have significant impact on the static system of the structure are identified for uniform box or tubular culvert bridges (the most common structure forms) according to (Håndbok V440 - Bruregistrering, 2014) and BRUTUS database. These components are selected as C (substructure), D (superstructure) and H (equipment).

The FMEA methodology has been used for these components to find the relevant failure modes, causes, mechanism and effects. For the components C and D, failure modes can be thinning, creep, rupture, bending, cracking, fracture, wear and discoloration. However, for the component H, the failure modes can vary based on the different characteristics of the subcomponents.

Based on component characteristics and the FMEA analysis done for these components and their subcomponents, there can be generally nine common failure modes identified. These failure modes are:

- Thinning
- Creep
- Rupture
- Bending
- Cracking
- Fracture
- Wear
- Discoloration
- Sagging

- **FURTHER STUDIES**

As some recommendations for further studies, it can be suggested to collect the relevant database for entire Norway. In that case, it might be possible to discuss the mentioned concepts more in depth. In addition, it could be possible to develop statistical models to find the corresponding relations between different involving factors.

It is also recommended to utilize the relevant database for the risk-based maintenance planning based on different standards and guidelines. Thus, it can be possible to detect the current problems and develop some improvements in the maintenance and inspection of bridges in Trondheim.

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APPENDIX A: DATA

Table A- 1: The actual data given by SVV.

Code	Name	Category	Form	Material	Cons. year	Length	Climate zone	Accessibility	The worst damage degree	Road type	Usage load
16-0172	Brattørbrua	Vegbru	Rullebru, bjelker	Steel	1939	32	Inner coastline	No need, Other	6 V	IKKE	Bk 6/28
16-0439	Sluppenbrua	Vegbru	Bjelkebru, valsede bjelker	Steel	1954	82	Inland	Boat, No need, bridge lift, Other	16 B	IKKE	Bk 10/50
16-0051	Tillerbrua	Vegbru	Hvelvbru med hel overmur, alt murt i mørtel	Stone	1912	26.7	Inland		12 V	B	Bk 10/50
16-1239	Støre Driftsvegbru	Vegbru	Bjelke-platebru, massiv, m/vinger	Insitu Reinforced Concrete	1988	40.4	Inland	No need	4 T	B	Bk 10/50
16-0016	Trolla	Bru i fylling	Kulvert, plassprodusert, m/sålefundament	Insitu Reinforced Concrete	1979	4	Inland	Other	6 B	A	Bk 10/60
16-0032	Sagelv Østre	Vegbru	Platebru, massiv, m/overliggende kantforsterkning	Insitu Reinforced Concrete	1973	4.7	Inland	No need	6 B	A	Bk 10/60
16-0041	Osen Tappeløp	Vegbru	Hvelvbru med hel overmur, andre	Stone	1967	2.8	Inland	No need	2 V	A	Bk 10/60
16-0042	Sagelv Vestre	Vegbru	Platebru, massiv, m/overliggende kantforsterkning	Insitu Reinforced Concrete	1973	4.3	Inland	No need	1 V	A	Bk 10/60
16-0052	Bakke bru	Vegbru	Bj.bru, plateb., vari.h., klinkede m/nagleskjøter	Steel	1929	81	Inner coastline	No need	12 V	A	Bk 10/50
16-0082	Brå	Vegbru	Bjelkebru, valsede bjelker, HE-B u/samvirke	Steel	1933	53.5	Inland	bridge lift	12 T	A	Bk 10/60

16-0087	Osen	Vegbru	Kulvert, plassprodusert	Insitu Reinforced Concrete	1991	5	Inland	No need	4 V	A	Bk 10/60
16-0259	Kroppøyen	Vegbru	Platebru, massiv, rektangulært tverrsnitt	Insitu Reinforced Concrete	1941	6.2	Inland	No need	12 T	A	Bk 10/60
16-0298	Større Bru O/Krøtterv	Vegbru	Platebru, massiv	Insitu Reinforced Concrete	1941	3	Inland	No need	9 T	A	Bk 10/60
16-0347	Espås	Vegbru	Platebru, massiv	Insitu Reinforced Concrete	1948	4.75	Inland	No need	12 T	A	Bk 10/60
16-0394	Jernbanebrua	Vegbru	Klaffebru, enarmet, bjelker	Steel	1950	56.86	Inner coastline	Boat, Other, Climbing equipment	16 T	A	Bk 10/50
16-0406	Elgeseter	Vegbru	Bjelkebru, plassprodusert, konstant høyde m/samvirke	Insitu Reinforced Concrete	1951	200.9	Inland	No need, bridge lift, Other	9 B	A	Bk 10/50
16-0488	Gråstua 1	Vegbru	Platebru, massiv, andre	Insitu Reinforced Concrete	1958	7.3	Inland	No need		A	Bk 10/60
16-0514	Gråstua	Vegbru	Platebru, massiv, m/underliggende kantforsterkning	Insitu Reinforced Concrete	1959	8.2	Inland	No need	3 T	A	Bk 10/60
16-0520	Leirelva	Vegbru	Bjelkebru, valsede bjelker, HE-A u/samvirke	Steel	1959	35.8	Inland	No need	9 T	A	Bk 10/60
16-0701	Fotgj.U.G. V/Åsvegen	Bru i fylling	Kulvert, plassprodusert, m/sålefundament	Insitu Reinforced Concrete	1967	5.57	Inland	No need	6 T	A	Bk 10/60
16-0704	Fjøsvollan	Bru i fylling	Rør i fylling, korrugert, flatbunnet (lavprofil)	Steel	1967	3.2	Inland	No need	4 V	A	Bk 10/60
16-0707	Ladedalen	Vegbru	Ribbeplatebru (massiv over støtte)	Insitu Reinforced Concrete	1967	24.5	Inland	No need	12 T	A	Bk 10/60
16-0745	Bråli	Bru i fylling	Rør i fylling, korrugert, sirkulært	Steel	1968	3.65	Inland	No need	2 V	A	Bk 10/60

16-0772	Tonstad Bru O/G/Sykk	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1969	4.03	Inland	No need	4 T	A	Bk 10/60
16-0806	Havstad o/GSV	Bru i fylling	Kulvert, plassprodusert, m/sålefundament	Insitu Reinforced Concrete	1971	5.6	Inland	No need	4 T	A	Bk 10/60
16-0811	Moholt Bru O/Gang/S.	Bru i fylling	Kulvert, plassprodusert, m/sålefundament	Insitu Reinforced Concrete	1972	12.8	Inland		4 V	A	Bk 10/60
16-0817	Sluppen Viadukt	Vegbru	Bjelke-platebru, massiv, m/vinger	Insitu Reinforced Concrete	1972	171	Inland	No need, Other	9 V	A	Bk 10/60
16-0819	Hammer	Bru i fylling	Rør i fylling, korrugert, stående ellipse	Steel	1972	3.75	Inland	No need	12 B	A	Bk 10/60
16-0821	Leirelva Kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1972	5.1	Inland	No need	4 T	A	Bk 10/60
16-0868	Simensbrua O/Bedrift	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1975	7.6	Inland		4 V	A	Bk 10/60
16-0871	Sluppen Kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1975	14.85	Inland		9 T	A	Bk 10/60
16-0874	Eggan	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1975	10.25	Inland		6 T	A	Bk 10/60
16-0886	Kroppan Østre	Vegbru	Kassebru, konstant høyde, vertikale vegger	Insitu Reinforced Concrete	1975	402.5	Inland	Boat, No need, bridge lift	12 T	A	Bk 10/60
16-0889	Rampe 7 Kulv.O. Leir	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1975	8.2	Inland	No need	4 T	A	Bk 10/60
16-0910	Kroppanskogen Over R	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1976	25.31	Inland		6 V	A	Bk 10/60

16-0913	Nidelv bru	Vegbru	Bjelkebru, NOB/NOT	Insitu Prestressed Concrete	1976	203	Inner coastline	bridge lift, Other	9 B	A	Bk 10/60
16-0920	Kolstad O/GSV	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1976	5	Inland		6 T	A	Bk 10/60
16-0921	Bjørndalsbrua	Vegbru	Bj.bru, plateb., kon.h., sveiset m/frik.skj. u/samv.	Steel	1976	274	Inland	No need, bridge lift	9 T	A	Bk 10/60
16-0985	Flakk Vest	Vegbru	Bjelkebru, NOB, massivtverrsnitt	Insitu Prestressed Concrete	1979	32.5	Inland		4 B	A	Bk 10/60
16-0995	Leirbrua o/GSV	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1979	5.36	Inland		4 T	A	Bk 10/60
16-0996	Leirbrua	Bru i fylling	Rør i fylling, korrugert, flatbunnet (lavprofil)	Steel	1979	5.59	Inland		4 V	A	Bk 10/60
16-1015	Buran kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1980	5.8	Inland	No need	4 T	A	Bk 10/60
16-1043	Ringvålvegen Skiund.	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1981	5.63	Inland		4 T	A	Bk 10/60
16-1046	Jakobsli o/GSV	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1980	3.3	Inland		6 B	A	Bk 10/60
16-1047	Teslimyr kulvert	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 1	Insitu Reinforced Concrete	1990	3.3	Inland		2 V	A	Bk 10/60
16-1057	Formo O/E6	Vegbru	Bjelkebru, NIB	Insitu Prestressed Concrete	1982	63.5	Inland	bridge lift	4 V	A	Bk 10/50
16-1094	Stoneberget o/GSV	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1983	4.5	Inland	No need	4 T	A	Bk 10/60

16-1097	Ytre Ringveg o/GSV	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1983	4.46	Inland	No need	6 T	A	Bk 10/60
16-1100	Prøven	Bru i fylling	Rør i fylling, korrugert, flatbunnet (lavprofil)	Steel	1983	8.45	Inland	No need	4 T	A	Bk 10/60
16-1103	Kroppan	Bru i fylling	Rør i fylling, korrugert, flatbunnet (lavprofil)	Steel	1983	8.2	Inland	No need	6 T	A	Bk 10/60
16-1106	Okstad Jordbruksund.	Bru i fylling	Rør i fylling, korrugert, flatbunnet (lavprofil)	Steel	1973	4.55	Inland	No need	6 T	A	Bk 10/60
16-1109	Østre Rosten Kulvert	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1983	4.45	Inland	No need	4 T	A	Bk 10/60
16-1144	Tonstad O/Ytre Ringv	Vegbru	Bjelkebru, NIB	Insitu Prestressed Concrete	1983	54.2	Inland	bridge lift	6 T	A	Bk 10/60
16-1150	Værebrua o/GSV	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1983	3.3	Inland	No need	6 V	A	Bk 10/60
16-1181	Ringvålvegen Jordbru	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1985	5.6	Inland	No need	4 T	A	Bk 10/60
16-1184	Lerkendal Søndre o/GSV	Vegbru	Platebru, massiv, skrå platekanter	Insitu Reinforced Concrete	1985	16.1	Inland	No need	6 T	A	Bk 10/60
16-1185	Lerkendal Nordre o/GSV	Vegbru	Platebru, massiv, skrå platekanter	Insitu Reinforced Concrete	1985	16.1	Inland	No need	9 T	A	Bk 10/60
16-1203	Rotvollhaugbrua nord	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1986	63.2	Inland	No need	6 V	A	Bk 10/60
16-1206	Madsjøbrua øst	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1986	55	Inland		6 V	A	Bk 10/60
16-1220	Løkkegt kulvert o/g-s vei	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1984	3.63	Inland		6 T	A	Bk 10/60

16-1224	Sør-Nypan Kulvert	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1987	4.62	Inland		4 V	A	Bk 10/60
16-1228	City syd vegbrua til E6	Vegbru	Bjelkebru, NIB, forspente u/samvirke	Insitu Prestressed Concrete	1987	50.21	Inland	No need, bridge lift	4 T	A	Bk 10/60
16-1234	Reppebrua	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1988	68.3	Inland	No need	9 T	A	Bk 10/60
16-1236	Vikelva Kulvert	Bru i fylling	Kulvert, plassprodusert, m/sålefundament	Insitu Reinforced Concrete	1988	3.6	Inner coastline	Other	4 V	A	Bk 10/60
16-1237	Govatsmark Kulvert	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1988	4	Inland		12 T	A	Bk 10/60
16-1238	Være Krøtterundergan	Bru i fylling	Rør i fylling, korrugert, sirkulært	Steel	1988	2.8	Inland		4 V	A	Bk 10/60
16-1240	Gjervan Jordbrukskul	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1988	4.6	Inland		9 T	A	Bk 10/60
16-1253	Presthusvegen Øst o/GSV	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1988	4.6	Inland	No need	2 V	A	Bk 10/60
16-1255	Sverre Svendsensveg o/GSV	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1988	4.39	Inland		4 V	A	Bk 10/60
16-1258	Fossen O/Gang og Syk	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1988	4.39	Inland	No need	4 V	A	Bk 10/60
16-1259	Ranheim Vestre O/GSV	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1988	4.4	Inland	No need	4 T	A	Bk 10/60
16-1262	Sandmoen	Vegbru	Bjelkebru, NIB, forspente m/samvirke	Insitu Prestressed Concrete	1988	77	Inland	bridge lift	6 V	A	Bk 10/60

16-1265	Solbakkenbrua	Vegbru	Bjelkebru, plassprodusert, overliggende bjelker	Insitu Reinforced Concrete	1988	35	Inland		2 V	A	Bk 10/60
16-1267	Stavset	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1988	5.6	Inland		4 V	A	Bk 10/60
16-1303	Jotunvegen o/GSV i Utleirvegen	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1991	4.6	Inland		4 T	A	Bk 10/60
16-1304	Klæbuvegen Kulvert	Bru i fylling	Kulvert, plassprodusert, andre	Insitu Reinforced Concrete	1990	10.18	Inland		12 B	A	Bk 10/60
16-1305	Nardo Skole O/G- S vei	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1990	4.65	Inland		9 M	A	Bk 10/60
16-1306	Stoneaunet o/GSV	Bru i fylling	Kulvert, prefabrikert	Insitu Reinforced Concrete	1992	3.4	Inland		1 B	A	Bk 10/60
16-1350	Kroppan Vestre	Vegbru	Kassebru, konstant høyde, vertikale vegger	Insitu Reinforced Concrete	1990	384.5	Inland	Boat, bridge lift	6 V	A	Bk 10/60
16-1354	Lerkendal G/S bru	G/S-bru	Bjelkebru, ikke normerte elementer, andre	Insitu Reinforced Concrete	1991	27	Inland	No need, Scissor lift	9 B	A	Bk 10/50
16-1357	Nardo Vestre	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1991	23.9	Inland	No need	6 T	A	Bk 10/60
16-1358	Nardo Østre	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1991	25	Inland	No need	4 T	A	Bk 10/60
16-1360	Røllikvegen	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1991	4.7	Inland		4 T	A	Bk 10/60
16-1362	Klefstad	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1991	3.66	Inner coastline	No need	1 T	A	Bk 10/60

16-1363	Spongdal	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1991	17	Inland		4 B	A	Bk 10/60
16-1369	Moholtbrua	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1992	47.1	Inland		6 T	A	Bk 10/60
16-1374	Valøyvegen g/s-veg kulvert	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	1992	4.36	Inland	No need	4 T	A	Bk 10/60
16-1403	Grillstadtunnel portal sør, nordgående	Tunnel/ Vegoverbygg	Tunnelportal, sirkulært tverrsnitt	Insitu Reinforced Concrete	1988	0	Inland	No need, bridge lift	1 V	A	Bk 10/50
16-1422	Ravnkloløpbrua (ny)	Vegbru	Bj.bru, plateb., kon.h., sveiset m/doble steg m/samv.	Insitu Reinforced Concrete	2010	51.8	Coastal	No need, Other	1 M	A	Bk 10/60
16-1432	Angeltrøa Kulvert	Bru i fylling	Hvelv i fylling, prefabrikert, Matiere	Insitu Reinforced Concrete	1999	5.68	Inland	No need	4 T	A	Bk 10/60
16-1434	Reitgjerdet kulvert	Bru i fylling	Hvelv i fylling, prefabrikert, Matiere	Insitu Reinforced Concrete	1999	8	Inland		6 T	A	Bk 10/60
16-1436	Tunga kulvert	Bru i fylling	Hvelv i fylling, prefabrikert, Matiere	Insitu Reinforced Concrete	1999	11.8	Inland		4 T	A	Bk 10/60
16-1444	Bratsbergveibrua	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1996	41.23	Inland		6 T	A	Bk 10/60
16-1445	Bratsbergveien Rampe	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	1996	28	Inland		6 T	A	Bk 10/60
16-1507	Dalgårdbrua	Vegbru	Bj.bru, plateb., kon.h., sveiset m/frik.skj. m/samv.	Steel	1996	180	Inland	bridge lift	6 V	A	Bk 10/60
16-1508	Kystadbrua	Vegbru	Bj.bru, plateb., kon.h., sveiset m/frik.skj. m/samv.	Steel	1996	96	Inland	bridge lift	9 V	A	Bk 10/60

16-1515	Voldsminde kulvert	Vegbru	Kulvert, prefabrikert, elementkulvert nr. 1	Insitu Reinforced Concrete	1994	5.8	Inland	No need	4 T	A	Bk 10/60
16-1530	Løvåsmyrbrua	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	1999	5.8	Inland	No need	4 T	A	Bk 10/60
16-1563	Kystadbrinken fotgj.underg.	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1997	4.92	Inland		4 V	A	Bk 10/60
16-1565	Byåsen skole Kulvert	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1997	5.92	Inland		4 T	A	Bk 10/60
16-1566	Smistad kulvert	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1997	4.62	Inland	No need	4 V	A	Bk 10/60
16-1567	Dalgård kulvert	Bru i fylling	Kulvert, plassprodusert, m/sålefundament og trykkbjelk	Insitu Reinforced Concrete	1997	4.62	Inland	No need	4 T	A	Bk 10/60
16-1581	Bergheimbrua g/s-veg kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2006	6.3	Inland	No need	1 V	A	Bk 10/60
16-1582	Stokkanbrua	Vegbru	Bjelkebru	Insitu Reinforced Concrete	1985	31	Inland	No need	6 T	A	Bk 10/60
16-1642	Skansenløpet tunnel	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2009		Coastal	No need, Other	4 T	A	Bk 10/60
16-1644	Trolla o/gsv	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	2002	4.4	Inland		4 T	A	Bk 10/60
16-1653	Ilsvikøra g/s-veg kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2006	6.51	Inland		4 V	A	Bk 10/60
16-1666	Rødde jordbruksundergang	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	2005	4	Inland		4 V	A	Bk 10/60

16-1672	Pirbrua	Vegbru	Klaffebru, toarmet, bjelker	Steel	2009	131.84	Coastal	No need	6 V	A	Bk 10/60
16-1675	Strandveiparken g/s-vegkulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2013		Inland	No need	6 V	A	Bk 10/60
16-1676	Strindheimkryssbrua	Vegbru	Ribbeplatebru (massiv over støtte)	Insitu Reinforced Concrete	2012		Inland	No need	4 V	A	Bk 10/60
16-1677	Leangbrua	Vegbru	Platebru, massiv, rektangulært tverrsnitt	Insitu Reinforced Concrete	2014	49.6	Inland	No need	12 T	A	Bk 10/60
16-1679	Falkenborg g/s-vegkulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2010	4.73	Inland	No need	4 V	A	Bk 10/60
16-1680	Falkenborgvegen g/s-veg kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2009	5.8	Inland	No need	6 T	A	Bk 10/60
16-1681	Strindheimskolen g/s-veg kulvert	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2012	3.6	Inland	No need	4 V	A	Bk 10/60
16-1689	Klett kulvert Nypansletta boligfelt	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	2008	3.4	Inland	No need	4 V	A	Bk 10/60
16-1693	Bromstadvegen g/s-vegkulvert	Vegbru	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2011	10.5	Inland	Other	1 V	A	Bk 10/60
16-1701	Cecilienborg gs-vegundergang	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2010	5	Inland	No need	4 M	A	Bk 10/60
16-1720	Sentervegen sørgående	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	56	Inland	No need	2 V	A	Bk 10/60
16-1723	Rostenbrua (over ringveg nord)	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	72	Inland	No need	1 V	A	Bk 10/60

16-1734	Rotvollhaugbrua sør	Vegbru	Bjelke-platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	63.9	Inland	No need	4 V	A	Bk 10/60
16-1735	Rotvollkryssbrua sør	Vegbru	Bjelkeramme, m/sålefundament	Insitu Reinforced Concrete	2013	23.85	Inland	No need		A	Bk 10/60
16-1736	Rotvollkryssbrua nord	Vegbru	Bjelkeramme, m/sålefundament	Insitu Reinforced Concrete	2013	29.64	Inland	No need	4 T	A	Bk 10/60
16-1738	Madsjøbrua vest	Vegbru	Bjelke-platebru, massiv	Insitu Reinforced Concrete	2013	73.5	Inland	No need	9 T	A	Bk 10/60
16-1750	Sentervegbrua nordgående	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	56	Inland	No need	2 V	A	Bk 10/60
16-1753	Rostenbrua nordgående	Vegbru	Platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	72	Inland	No need	1 V	A	Bk 10/60
16-1766	Rotvoll g/s-veg undergang nord	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2013	6	Inland	No need	3 M	A	Bk 10/60
16-1791	Rotvoll g/s-veg undergang sør	Bru i fylling	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2013	9.47	Inland	No need	4 T	A	Bk 10/60
16-1798	Madsjø g/s-vegkulvert	Bru i fylling	Kulvert, prefabrikert	Insitu Reinforced Concrete	2002		Inland	No need	4 V	A	Bk 10/60
16-1801	Trolla g/s-vegkulvert under Bynesv	Bru i fylling	Kulvert, prefabrikert, elementkulvert nr. 2	Insitu Reinforced Concrete	2017	4.6	Inner coastline	No need	4 V	A	Bk 10/60
16-1900	Ristanbrua	Vegbru	Bjelkebru, NOB, massivtverrsnitt	Insitu Reinforced Concrete	1990	9	Inland	No need	16 T	A	Bk 10/60
16-0177	Nidareid halvbru	G/S-bru	Bjelkebru, plassprodusert, overliggende bjelker	Insitu Reinforced Concrete	1983	50	Inland	Other	6 T		

16-0987	Kroppøyen G/S Bru	G/S-bru	Bjelkebru, platebærere, konstant høyde	Steel	1979	14	Inland		6 V		
16-1622	Marienborgtunnelen, portal. Nord	Tunnel/ Vegoverbygg	Tunnelportal, rektangulert tverrsnitt	Insitu Reinforced Concrete	2007	0	Inland		1 M		
16-1654	Stoneberget tunnellen, portal	Tunnel/ Vegoverbygg	Tunnelportal, sirkulært tverrsnitt		2007	0	Inland		4 V		
16-1657	Ilsvik løsmassetunnel vest	Tunnel/ Vegoverbygg	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2007	0	Inland	Other			
16-1670	Rv706 Strindheim tunnelportal vest	Tunnel/ Vegoverbygg	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2014	0	Inland		4 V		
16-1671	Rv706 Strindheim tunnellportal øst	Tunnel/ Vegoverbygg	Kulvert, plassprodusert, m/bunnplate	Insitu Reinforced Concrete	2011	0	Inland				
16-1685	Portalbygg tunnelrampe Strindheimskrysse	Tunnel/ Vegoverbygg	Tunnelkonstruksjon, rektangulært tverrsnitt u/bunnpl.	Insitu Reinforced Concrete	2011	0	Inland	Other	1 T		
16-1711	Strindvegen g/s-vegbru	G/S-bru	Platebru, massiv, skrå platekanter	Insitu Reinforced Concrete	2011	16.1	Inland		4 V		
16-1713	Stavne Insitu Reinforced Concretetunnel	Tunnel/ Vegoverbygg	Miljøtunnel	Insitu Reinforced Concrete	2011	0			2 T		
16-1715	Thaulow g/s-vegbru	G/S-bru	Sprengverksbru	Insitu Reinforced Concrete	2012	31.8	Inland		4 V		
16-1719	Vinterveien g/s-vegbru	G/S-bru	Bjelke-platebru, massiv, m/vinger	Insitu Reinforced Concrete	2013	152.14	Inland	No need	9 T		
16-1721	Sentervegen g/s-vegbru	G/S-bru	Bjelke-platebru, massiv, m/vinger	Insitu Prestressed Concrete	2015	130	Inland	No need	4 V		

16-1724	City Syd g/s-vegbru	G/S-bru	Bjelke-platebru, massiv, m/vinger	Insitu Prestressed Concrete	2015	56	Inland	No need				
16-1725	John Aases g/s-vegbru	G/S-bru	Bjelke-platebru, massiv, m/vinger	Insitu Prestressed Concrete	2015	30	Inland	No need	4 V			
16-1737	Rotvollbrua g/s-vegbru	G/S-bru	Platebru, massiv, andre	Insitu Prestressed Concrete	2013	92.2	Inland	No need	9 V			
16-1739	Svingbrua	G/S-bru	Svingbru, ulikearmet	Steel	2014		Coastal		6 T			
16-1930	Grillstadtunnel portal nord, nordgående	Tunnel/ Vegoverbygg	Tunnelportal, sirkulært tverrsnitt	Insitu Reinforced Concrete	1988	0		No need	4 T			
16-1931	Grillstadtunnel portal sør, sørgående	Tunnel/ Vegoverbygg	Tunnelportal, sirkulært tverrsnitt	Insitu Reinforced Concrete	1988	0		No need, bridge lift	6 V			
16-1932	Grillstadtunnel portal nord, sørgående	Tunnel/ Vegoverbygg	Tunnelportal, sirkulært tverrsnitt	Insitu Reinforced Concrete	1988	0		No need	4 V			
50-0014	Prinsensgt g/s-vegkulvert	Annen byggv.kategori			2006							