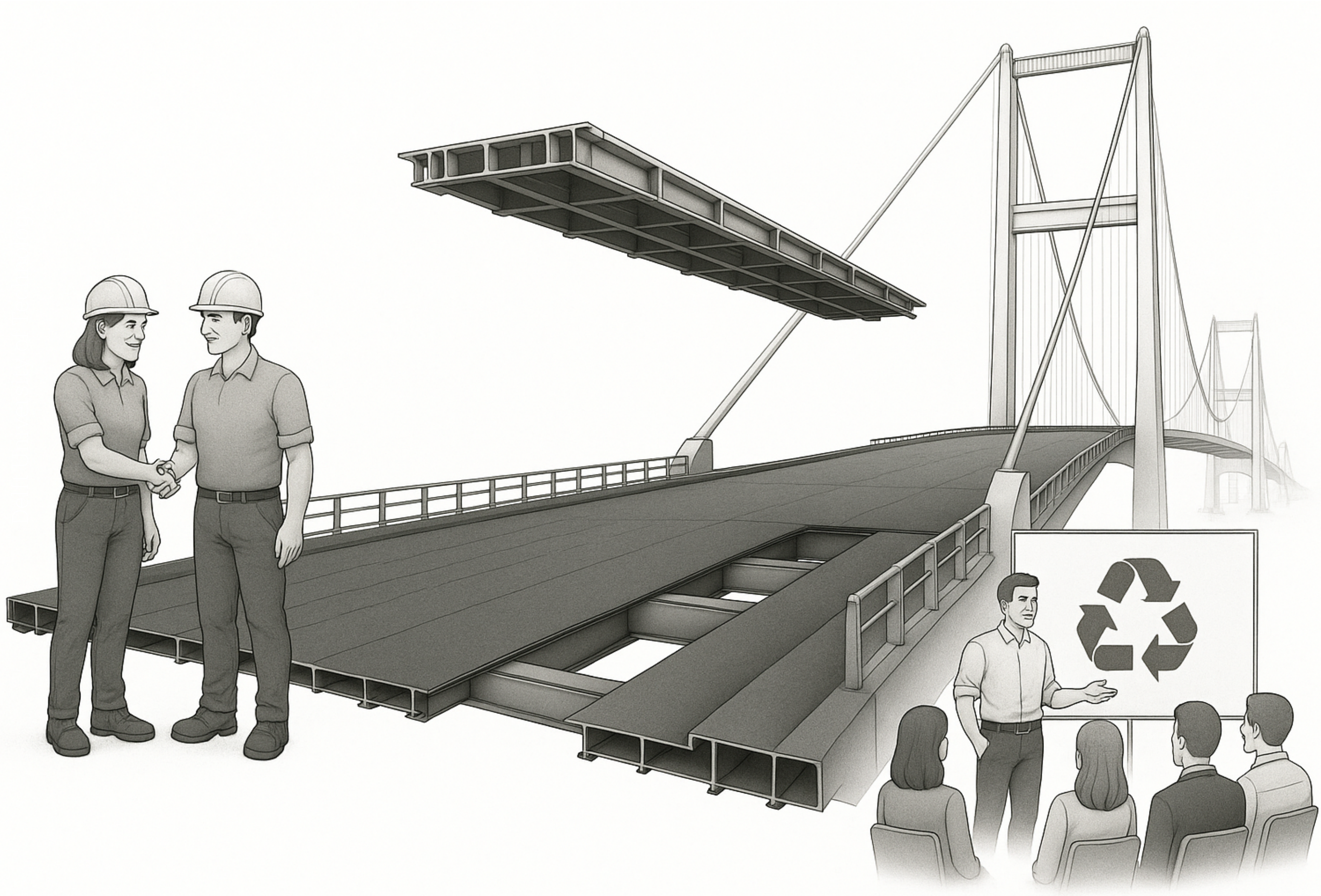
Forging the path to reuse

A study on what is technically and societally needed to stimulate the adoption of reused steel bridge components by stakeholders in the construction industry.

M.A. Schuurmans



TU Delft

SWECO

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A study on what is technically and societally needed to stimulate the adoption of reused steel bridge components by stakeholders in the construction industry.

by

M.A. Schuurmans

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 11-07-2025.

Civil Engineering	Structural Engineering
Construction Management and Engineering	Projects & People

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Project Duration:	September 2024 - July 2025
Faculty:	Faculty of Civil Engineering and Geosciences, Delft
Cover:	Based on Canam Bridges - Accelerated bridge construction (Bridges, 2014) adapted with the help of ChatGPT (OpenAI, 2025)

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Preface

This thesis marks the final step towards obtaining my Master's degrees in Civil Engineering (CE) and Construction Management and Engineering (CME). The opportunity to combine both programmes has enriched the final product, resulting in a multidisciplinary thesis with a more meaningful outcome.

Furthermore, this thesis concludes six years of studying at TU Delft, a period in which I gained a lot of academic knowledge, but also look back on great memories and valuable experiences. Over the past months, I had the opportunity to delve into the topic of reusing steel bridge components, a subject that is both technically challenging and societally relevant. This graduation project has not only deepened my understanding of the topic itself, but has also strengthened my research skills and professional independence.

During the writing process, I received valuable support and feedback. I would like to thank Sweco Nederland for allowing me to conduct my research and for providing their knowledge, facilities, and software. In particular, I would like to thank Nick Montenij for his relevant insights and continuous enthusiasm throughout all phases of the project. I would also like to thank William Klepper for his practical perspectives and Niels van der Woude for his assistance with modelling in the FEM software. Moreover, I want to thank the other colleagues at Sweco for their genuine interest and for creating a pleasant and motivating working atmosphere.

Additionally, I want to thank my supervisors from TU Delft. From the CME perspective, I am grateful to Erik-Jan Houwing and Marian Bosch-Rekveldt for their helpful suggestions and constructive feedback during our meetings, which helped me to broaden my engineering perspective and better understand the societal dimension of my work. From the CE perspective, I would like to thank Florentia Kavoura and Bert Sluys for their technical insights and critical reflections, which contributed to a more focused direction in my research. I also sincerely thank all interviewees for their time and the valuable discussions they provided during our conversations. Lastly, I would like to thank my boyfriend, friends, and family for their continuous support and encouragement throughout the process.

M.A. Schuurmans
Delft, July 2025

Executive summary

A lot of bridges in the Netherlands were constructed in the decades after World War II. These bridges are now reaching the end of their service life and are therefore largely due for replacement or renovation. While the functionality of these bridges may be declining, some of their individual components still contain substantial structural value. In light of growing circularity ambitions, the reuse of these components presents a potential opportunity to reduce emissions and make the most of this residual value. Despite its advantages, steel bridge component reuse has not yet become common practice in the Netherlands. This thesis explores why that is the case and what is needed to stimulate broader adoption. The main research question guiding this research is: *"What is needed to stimulate the adoption of steel bridge component reuse among stakeholders in the Dutch construction industry?"*

To answer this question, a mixed-method approach was used, combining a review of academic literature with a technical case study, and qualitative interviews. The literature research has revealed five obstacles that span technical, regulatory, economic, and cultural domains. Firstly, sourcing of the steel is difficult because material properties are sometimes uncertain. It should be available at the right place and time with the proper quality, meaning supply and demand must align. Secondly, there is currently a lack of design standards tailored to the assessment of steel reuse from infrastructure. All existing Eurocodes focus on designing with new steel, and while the NTA 8713 offers guidance for buildings, it excludes fatigue-sensitive bridge components. Thirdly, there is a lack of regulations within the European Union, such as CE marking procedures, as marketing products without this mark is not possible. Fourthly, there is cost uncertainty as reuse is often more expensive due to testing, disassembly, and unpredictability in logistics. Finally, reuse requires trust and coordination throughout the supply chain, yet many stakeholders remain hesitant. This behavioral resistance is often rooted in concerns over quality and unfamiliarity with reuse processes.

To address the technical gap of the lack of design guidelines for assessing reuse potential from steel bridge components, such a standard was developed on the basis of a case study, namely the Freebrug in Oude Pekela. To allow for a focused yet broadly applicable assessment, the study first zoomed out to examine general bridge types in the Netherlands and then narrowed the focus to movable bridges. Within this selection, the Orthotropic Steel Deck (OSD) was chosen for further investigation of reuse potential. Based on the literature, the most critical failure mechanisms for OSDs are corrosion, fatigue, and the combination of these, which is also known as Corrosion Fatigue. Corrosion is described as the process in which oxygen deteriorates the outer layer of the steel. Fatigue is the progressive degradation of a component caused by fluctuating stress over an extended duration of time. The synergistic effect of both mechanisms may lead to greater damage than if they occur separately. These failure mechanisms should be considered to assess the condition of the steel after its first service life.

A Finite Element Model was created in which both continuous and discontinuous trough variants of the OSD were modeled. The loading history was estimated by Sweco, and the relevant damage mechanisms and described future scenarios were incorporated. The model was verified through stress checks and damage number calculations at critical weld locations. These critical weld locations turned out to be the weld between trough and deck and weld between trough and cross beam. The results showed that all damage numbers are below one, suggesting that technical reuse is possible even when damage is present.

From this case study, it is discovered what is required to determine the condition of steel from infrastructure, and how, based on the damage, intended future use scenarios are feasible or not. The key steps in assessing the reuse potential are:

1. Initial data: Collect all original data of the donor structure at the time of delivery, including drawings, materials, and year of construction.
2. Service life data: Determine the condition of the steel by mapping the damage caused by the

identified mechanisms using calculation models.

3. Future possibilities: Translate the identified damage into a feasible reuse option by checking whether the component still meets requirements for a proposed new application

If not, technical measures such as reducing service life, limiting axle loads, placing the component in a lower corrosivity class, changing function, or 'LEGOliseren' can be considered. This structured approach transforms reuse from an ambition into a procedure.

To complement the technical study, the thesis also investigates the obstacles from the literature study from the other domains. To find out whether and how these issues manifest in practice, sixteen semi-structured interviews were conducted with actors from across the Dutch construction supply chain, including clients, contractors, engineering consultancy firms, steel manufacturers, demolition contractors, and research and knowledge firms.

The interview data revealed a total of nineteen distinct obstacles, again stemming from various domains. Fourteen of these, including contractual limitations and lack of knowledge of clients, were not in the literature. These findings might indicate that the reuse knowledge in practice is moving beyond the topics so far described in literature. Furthermore, the frequency of the obstacles from interviews is counted and it turns out that two of those were mentioned by almost all interviewees, namely the 'Availability of steel' (mentioned in all 16 interviews) and 'Negative attitudes' (mentioned 13 out of 16 times). These are referred to as 'pillars' in the analysis, since the interview data shows that these pillars are often symptoms of deeper underlying obstacles, rather than isolated ones.

At the same time, the interview data reveals that not all theoretical obstacles are equally present in practice. The obstacle 'Lack of design guidelines' is widely emphasized in academic work, but mentioned by only approximately half of the interviewees (9 out of 16 times). Similarly, while 'Cost uncertainty' is often highlighted in literature as a hurdle, interviewees present mixed views (mentioned 7 out of 16 times). For some, costs are a decisive issue, while others consider them manageable, especially when reuse aligns with sustainability ambitions. The most notable divergence between theory and practice concerns the obstacle 'Lack of EU regulations' (mentioned 5 out of 16 times). Nine interviewees disagreed with this literature-based obstacle. This may indicate either a lack of awareness or a tendency to view legal challenges as more abstract or distant compared to technical and logistical ones.

Next, it was explored how these obstacles might be addressed according to interviewees. Across the interviews, 15 distinct strategies are proposed, again ranging from technical measures to coordination mechanisms and cultural intervention. Three strategies were mentioned most frequently. These are: 'make reuse a requirement in tenders' (12 out of 16 times), 'create storage locations for obtained supply' (10 out of 16 times), and 'train the supply chain through partnerships' (8 out of 16 times). These were proposed by different types of stakeholders across the chain, which might suggest that a shared strategic orientation is present within practice. At the same time, the full range of responses reflects a diverse set of proposed strategies and approaches. However, all these distinct strategies seem not to stand on their own. Some reflect similar underlying concerns and therefore simply counting mentions may not fully capture their systemic meaning. So to better understand how the strategies interrelate, and make sense of the wide range of strategies proposed by interviewees, the thesis developed an interpretative analysis in which the strategies were grouped into three clusters:

1. Rules and regulations
2. Collective learning and shared responsibility
3. Practical and physical logistics

This thematic clustering provides a lens to interpret reuse not just as a technical or organizational challenge, but as a systemic one. The added value of this systemic perspective is that it places the interview data within a broader understanding of how the sector is currently organized. Across these themes, a pattern of misalignment becomes visible. Firstly, awareness exists, but action often seems to lacks ownership. Furthermore, willingness is present, but structural reinforcement appears to be absent. Lastly, reuse is promoted, but may be expected to fit into conventional project routines. These insights may help explain why reuse tends to rely on front runners rather than institutionalised wider in practice. An illustrative road map is developed to offer one possible way to realign roles and responsibilities, and to encourage more coordination across the construction chain.

Finally, the findings suggest a shift in how reuse may be framed. Instead of expecting reuse to become fully risk-free through guidelines and regulation, the analysis shows that some doubts are rooted in the nature of reuse. his view aligns with critical reflections in recent literature and suggests that reuse adoption also requires space to deal with imperfections, rather than eliminating all concerns entirely.

In conclusion, this research shows that stimulating the adoption of reused steel bridge components requires both technical verification and systemic realignment. From a Structural Engineering perspective, the proposed design guideline offers a structured and reproducible method to assess the reuse potential of damaged components. From a Construction Management perspective, adoption is shaped by behavioural hesitation, fragmented responsibilities, and rigid project routines. While these two findings stem from different disciplines, they are closely intertwined in practice. Without a technical method, reuse is perceived as too risky by stakeholders. But even with such a method, broad adoption is unlikely if systemic conditions do not align. This thesis demonstrates that closing the technical gap is essential, but not sufficient on its own. Adoption also requires alignment across the supply chain, ranging from clients who request reuse, to engineers who can justify it, and contractors who are logistically prepared to implement it. By integrating both technical and managerial perspectives and acknowledging reuse as a system transition, this thesis contributes to making reuse a more realistic and actionable option for the Dutch construction industry.

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Nomenclature

Abbreviations

Abbreviation	Definition
CF	Corrosion Fatigue
CE	Circular Economy
EEA	European Economic Area
EU	European Union
FEM	Finite Element Modeling
FLM	Fatigue Load Model
LCA	Life Cycle Assessment
LM	Load Model
OSD	Orthotropic Steel Deck
SLS	Serviceability Limit State
ULS	Ultimate Limit State

Symbols

Symbol	Definition	Unit
A	Surface	$[m^2]$
α	Angle	$[°]$
b	Metal-environment-specific time exponent	$[-]$
D_C	Total corrosion attack	$[g/m^2a]$
D_{CF}	Damage number Corrosion Fatigue	$[-]$
D_F	Damage number fatigue	$[-]$
F	Force	$[kN]$
m	Inverse slope parameter	$[-]$
N	Amount of cycles until failure	$[-]$
$N_{fromSNcurve}$	Number of total allowed heavy vehicles according to S-N curve	$[-]$
N_{pas}	Total number of heavy vehicles at slow lane	$[-]$
$N_{remaining}$	Remaining allowed total amount of heavy vehicles	$[-]$
q_{ik}	Distributed traffic load	$[kN/m^2]$
Q_{ik}	Traffic load	$[kN]$
r_{corr}	Corrosion rate for the first year	$[g/m^2a]$
ρ	Density of steel	$[kg/m^3]$
S_i	Future scenario i	$[-]$
$\Delta\sigma$	Stress range	$[N/mm^2]$
σ_{10x10}	Stress for mesh size 10x10 [mm]x[mm]	$[MPa]$
σ_{25x25}	Stress for mesh size 25x25 [mm]x[mm]	$[MPa]$
$\sigma_{FLM,max}$	Maximum stress at intersection point	$[MPa]$
$\sigma_{FLM,min}$	Minimum stress at intersection point	$[MPa]$
σ_x^+	Normal tensile stress in x-direction	$[MPa]$

1
Introduction

1.1. Research context

Currently, the task of replacement and renovation of infrastructure poses a significant challenge within The Netherlands, or in Dutch the so-called: 'Vervangings & Renovatie opgave' (Vlist et al., 2016). Several bridges built after World War II, as shown in Figure 1.1, which are used for transportation and connectivity across the country, are reaching the end of their intended lifespan of 50 to 75 years (Adriaanse et al., 2020; Reitsema et al., 2020). Due to this aging and also more intensive use, many concrete and steel bridges need renewal to ensure their safety (Davis et al., 2019). One way of addressing this challenge could be to replace the bridges by completely designing new ones. However, significant emissions would be generated for producing steel components and concrete beams, making it an unpopular choice from a sustainability point of view (Allwood et al., 2010). A different way of construction without producing new materials is to reuse previous bridge components. Reusing construction components is not as straightforward as it seems, and currently, there are several obstacles to achieving acceptance of reuse, both in engineering and management. These challenges will need to be identified and addressed to ensure that construction components are given the opportunity to serve a second life.

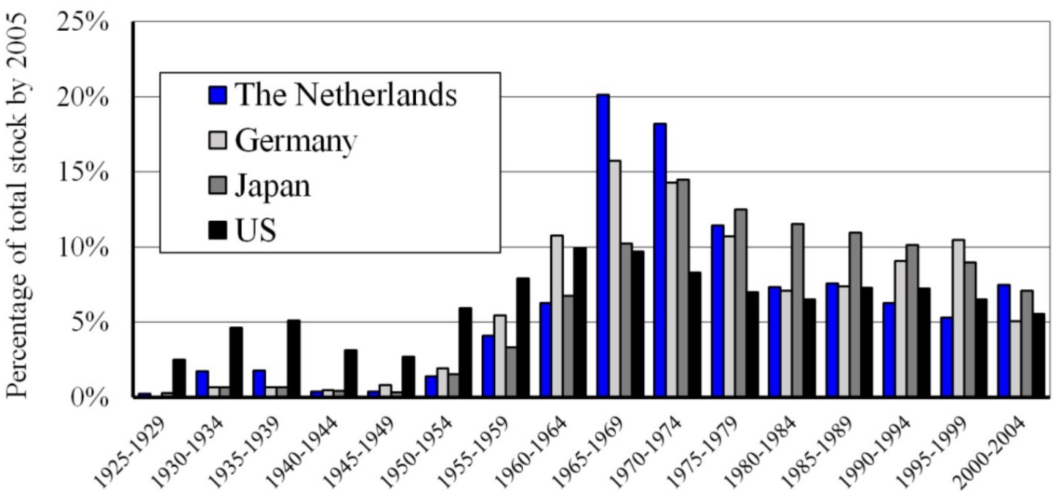


Figure 1.1: Overview of built bridges in The Netherlands, Germany, Japan and US (Allwood et al., 2010).

1.2. Research problem

From the current context, it becomes evident that the aging Dutch bridge stock must be renewed in a sustainable way. One suggestion is the reuse of steel bridge components. However, this concept remains still in the research phase, as challenges exist across multiple domains.

Literature identifies several obstacles to reuse, including technical, organizational, and stakeholder-related ones. The main technical obstacle is the lack of a design guideline to assess the reuse potential of steel bridge components. As a result, the remaining lifespan and material properties of reusable components can not be determined. Therefore, the lack of fixed or standardized design rules represents a key research gap that must be addressed to enable adoption.

In addition, the construction supply chain is characterized by a conservative mindset and resistance to change. Limited knowledge about the actual costs and performance of reclaimed components, combined with the absence of practical experience, results in a reduction of enthusiasm among stakeholders. For reuse to gain traction, stakeholders such as contractors, clients, suppliers, and structural engineers must have confidence that reclaimed steel components are reliable and available. While the existing literature acknowledges these obstacles, practical strategies for overcoming them and engaging the supply chain are still missing. This points to another key research gap that should be addressed in order to facilitate broader adoption.

In short, this thesis aims to bridge the gaps in technical shortcomings and stakeholder hesitance by identifying what is needed to stimulate the adoption of steel bridge component reuse in the Dutch construction industry.

1.3. Aim and objective

The aim of this research is to advance the understanding of how the adoption of reused steel bridge components can be increased. This will be achieved by addressing the existing technical gap through the development of a design guideline. In addition, the research aims to translate the practical strategies gathered into actionable insights on how these can be used to increase adoption among stakeholders in the construction industry.

1.4. Research scope

This research is being scoped, so that it is feasible within the prescribed time.

- **Steel bridges:** The research is focused solely on bridge components made of steel.
- **Scaling:** The focus for reuse is solely on components from the superstructure of the bridge on component level, so e.g. the foundation, abutments, and connections are outside the scope of this research.
- **Existing knowledge and parameters:** This study will reuse parameters found in academic literature and NEN-codes, and no experiments will performed to obtain those.
- **Case study**: The data and inspections regarding the bridge case, made available by Sweco are used, so no self on-site inspections are carried out.
- **Dutch construction supply chain:** Only the Dutch construction supply chain with associated parties and design regulations is analyzed.

1.5. Research questions

The main question that is posed in this research is:
What is needed to stimulate the adoption of steel bridge component reuse among stakeholders in the Dutch construction industry?

This is done by answering the sub-questions in the following order:

1. What is the state of the art of the adoption of reuse practices in the construction industry?
2. What types of damage can a steel bridge component already have that should be taken into account when assessing its reuse potential?

3. What are the key steps in assessing the technically safe reuse potential of steel bridge components?
4. What obstacles to the adoption of steel reuse are perceived by stakeholders, and what strategies do they propose in response?
5. How can the identified obstacles and strategies be understood in relation to broader systemic patterns in the construction industry?

1.6. Sweco context

Sweco is involved in this research as a supervising partner. The company has several specialized divisions, and the researcher is allowed to consult with experts from different departments to ask questions and receive in-depth feedback. In addition, since Sweco is an active player in the Dutch construction supply chain, this will help ensure that the research remains aligned with real-world conditions and industry practices. Lastly, the company provides access to data and inspection reports of a steel bridge, which serves as the case study in this research.

The research questions addressed in this study are directly relevant to Sweco. The company is actively exploring innovative solutions for the sustainable use of materials, and this research supports that aim. Sweco's portfolio includes many bridges that are part of the Dutch renovation and replacement (V&R) programme, and therefore it is valuable to investigate whether these structures still have reuse potential. Furthermore, as a market party with diverse clients, Sweco is also interested in the stakeholder-related processes and insights that could help stimulate sustainable practices within the sector.

1.7. Double degree explanation

This thesis has been written as part of a Double Degree programme, in which Civil Engineering and Construction Management and Engineering are combined. Therefore, several parts of this thesis are contributing for both degrees and serve the objectives of both programmes. In addition, there are also sections specific to each of the degrees to ensure the required level of depth is maintained. The overview and explanation for this distinction is given in Appendix A.

1.8. Structure of report

Figure 1.2 shows the different chapters of this thesis. The outline also presents the connection of the chapters to the sub-questions.

- Chapter 1 provides an introduction to the thesis, including the problem statement, main research question, and scope definition.
- Chapter 2 outlines the methodology used to address the main research question.
- Chapter 3 presents a literature review on the concept of reuse and the definitions related to it.
- Chapter 4 identifies the obstacles to the adoption of reuse in various areas as found in existing literature.
- Chapter 5 discusses the technical background of the study, detailing the type of component assessed for reuse and the relevant failure mechanisms.
- Chapter 6 elaborates on the case study that was analyzed within this research.
- Chapter 7 explains the process of building the Finite Element Model of the selected case study.
- Chapter 8 covers how the damage mechanisms can be incorporated into the model.
- Chapter 9 describes the model validation, including mesh sensitivity and the assumptions and simplifications made.
- Chapter 10 presents a design guideline for evaluating the reuse potential of steel bridge components.
- Chapter 11 analyses the interview data regarding obstacles and strategies collected from various stakeholders in the construction supply chain.

- Chapter 12 interprets the interview data by zooming out to the system to potentially stimulate adoption within the industry.
- Chapter 13 discusses how the findings can be placed in existing literature and explains limitations of the research.
- Chapter 14 concludes the findings of the thesis and recommendations for future work.

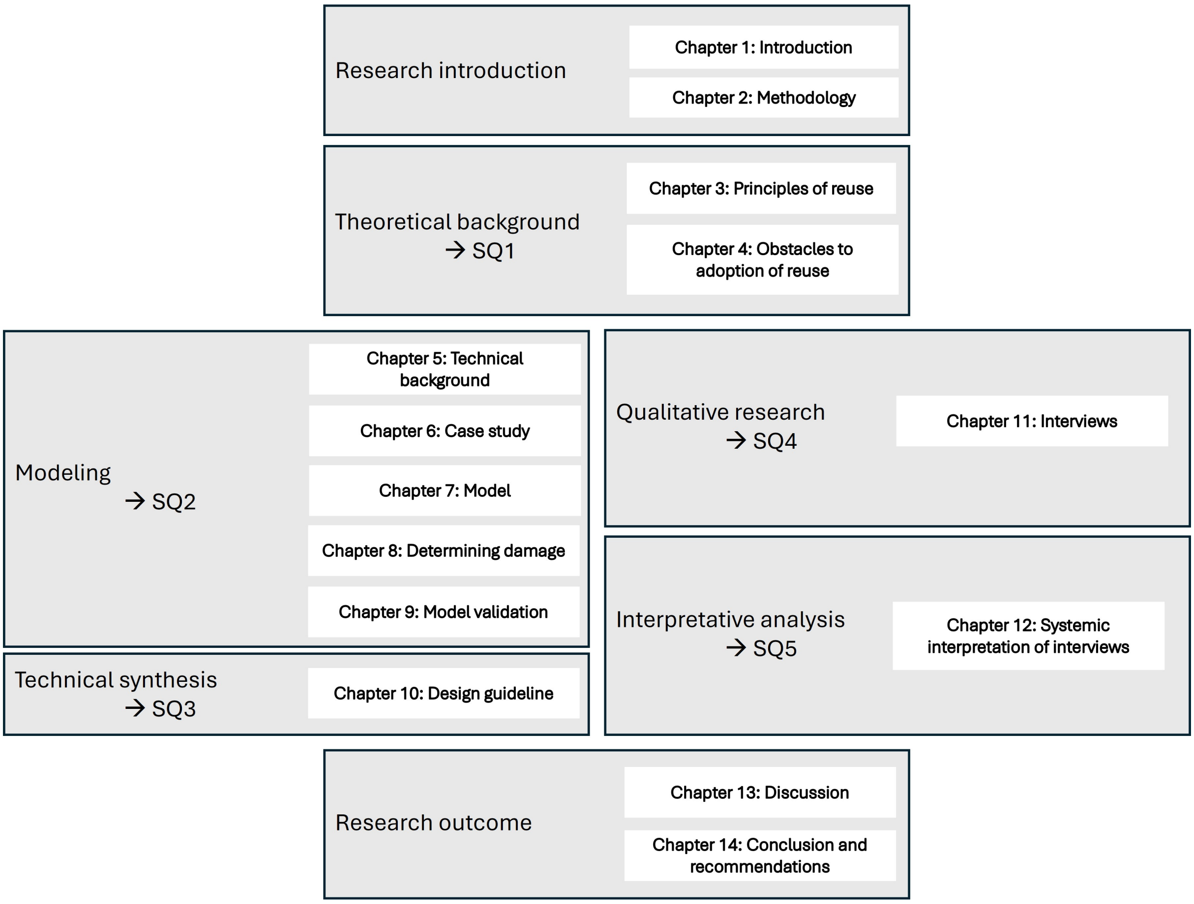


Figure 1.2: Developed thesis outline.

2 Methodology

This chapter delves deeper into the research methods that are used in this research. A literature review will be performed and the corresponding keywords are described. Besides to that, elaboration is given on the semi-structured interviews that are done and how the interviewees are chosen. Lastly, a case study research is done and it is explained why the chosen case study is relevant.

2.1. Mixed-method approach

This study will apply multiple research methods, in which a method is described as a research technique used to answer the research question (Walliman, 2021). This is also called a 'mixed-method approach', meaning a combination of qualitative and quantitative analysis will be applied, utilizing the strengths of both approaches. This is appropriate because one of the overarching goals of this thesis is to connect technical aspects with stakeholder perspectives. Quantitative data will be used to conduct structural verifications, while qualitative data will be gathered from interviews to capture the perspectives and experiences of stakeholders. Both types of data are necessary to formulate a comprehensive answer to the main research question. The process of obtaining this data can be divided into three types of research, which will be further explained below. An overview of these three types is presented in Figure 2.1.

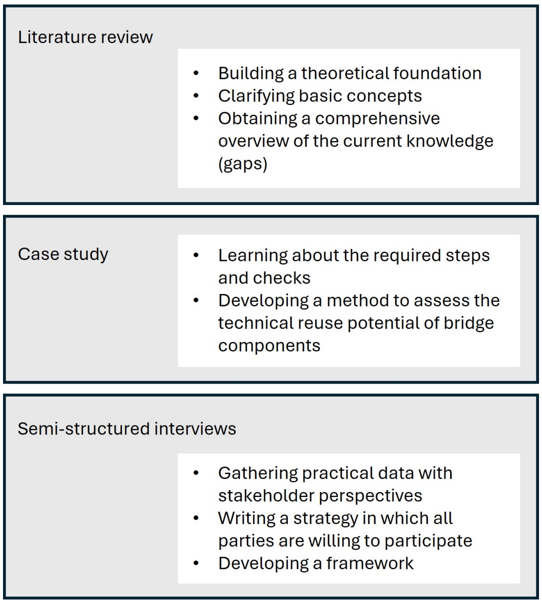


Figure 2.1: Developed overview with different methods.

2.2. Literature review

The first research method applied is a literature review, which involves reading and analyzing academic articles and journals. A literature review typically begins with a broad approach, aiming to capture the 'full' scope of available information. This should provide a general understanding of the topic before narrowing down to more focused and scoped areas. For this thesis, the foundation will begin with a broad understanding of reuse, outlining what reuse entails and its different forms. The focus will then narrow specifically to steel reuse. The research will further zoom in to explore why steel reuse is not yet widely practiced, identifying obstacles and challenges currently present.

The TU Delft repository can be used to explore theses completed by previous students to discover the state of the art in this research area. In addition to the TU Delft repository, several academic search engines tailored to research articles and papers will be used, including Google Scholar, ResearchGate, Semantic Scholar, and ScienceDirect.

For each step in the literature review, different keywords will be applied. The first keywords for looking into the basic principles of steel reuse and its benefits will include 'steel reuse principles' OR 'steel reuse basics' OR 'benefits of steel reuse'. After establishing this more general understanding, the focus is narrowed to explore challenges in the steel reuse supply chain. Keywords for this phase include 'obstacles steel reuse,' 'barrier steel reuse,' 'challenges steel reuse,' 'reuse design standards', and 'reuse cost'.

For the technical part, other keywords are used, namely 'types of bridges Netherlands' OR 'movable bridges' OR 'orthotropic steel decks' OR 'failure mechanisms steel' OR 'fatigue behavior steel' OR 'Wöhler curve' OR 'brittle fracture' OR 'ductile fracture' OR 'corrosion' OR 'corrosion susceptible locations' OR 'creep steel' OR 'buckling plates' OR 'corrosion fatigue'.

Ultimately, the literature review will form a foundation for the research, clarifying the basic concepts and providing a comprehensive overview of the current knowledge (state of the art). It will help identify existing gaps in the field. By the end of these chapters, a solid theoretical basis on reused steel and its obstacles will be established, which will later on also be enriched with practical insights from interviews.

2.3. Case study research

The next step in this thesis is a case study research. According to the performed literature review, there are technical concerns regarding reuse, and performing structural assessments is a major obstacle. There is a need to develop a method to assess the reuse potential of bridge components. This will be done in this thesis based on a case study of a steel bridge.

The selected case study was chosen in collaboration with experts from Sweco. Several criteria were used to choose a suitable case study, namely:

- The case study bridge should represent a 'common*' bridge type in the Netherlands, ensuring that the method of reuse assessment can be applied on a wider scale rather than being limited to a specific situation.
- The bridge must be made of steel.
- A set of drawings must be available so that a Finite Element Model can be created and structural verifications can be carried out based on these drawings.
- The loading history must be known to perform fatigue assessments.

**A common bridge type in the Netherlands can be identified through literature review or selected based on expert judgment. Key factors that should be considered are the span of the bridge and its structural components.*

2.3.1. Developing method through case study

The following steps need to be taken to ultimately develop a method for assessing the reuse potential of bridge components.

The first step is to analyze the available archive of the chosen case study and component for analysis. The created drawings will serve as the basis for the FE model to be developed. The FE model should also include the support conditions and applied loads. The loads to be considered are at least self-weight and traffic load, and it will need to be evaluated which other factors may influence the results. The loads will be combined into load combinations with corresponding safety factors. Once all these steps are completed, the basic model will be established.

Based on this basic model, verifications can be performed to identify critical stress locations in the analyzed component. Damage can then be added based on the failure mechanisms identified in the literature study. The model will need to be checked after the addition of damage to see whether it still meets the requirements. This will provide information on the reuse potential.

The final step is to validate the model of the case study to ensure that the conclusions drawn from the model reflect what they claim to represent. This will first be done by performing a mesh validation to determine the cell size for the calculations. This depends on the accuracy of the results and the associated runtime, and an optimal size should be chosen.

Subsequently, the assumptions and simplifications must be explained. This will highlight the limitations of the model and confirm why some simplifications are allowed. If they are not, the impact on the results will need to be addressed.

Ultimately, based on the case study, an overview will be developed, outlining the step-by-step process for assessing a bridge component for reuse.

2.3.2. Drawing conclusions from one case study

A case study is considered a useful approach to observe a certain phenomenon within a specific time or context. It is a relevant research method when it is beneficial to examine a problem within its natural real-life setting (Crowe et al., 2011). However, it should be noted that applying a single case study does not guarantee that the findings will be applicable in other situations, because it only reflects the outcome under the specific case study conditions. Although one case study does not provide a strong foundation for generalization, it can still be analyzed for its methodology and approach. This aligns well with this thesis in which there is a need to develop a method to assess the reuse potential of bridge components and therefore justifies the relevance of conducting a case study.

2.4. Semi-structured interviews

Besides theoretical data, also empirical data is obtained in this thesis. This is done by conducting interviews with experts in the construction industry to collect their perspectives and practical experiences. This empirical data is used to potentially supplement and/or confirm the findings from the literature review.

Before starting to invite interviewees and setting up the interviews, approval from the Human Research Ethics Committee (HREC) was first obtained. This is mandatory for all theses at TU Delft where data is collected from Human Research Subjects. Once this approval was obtained, the interviews were set up.

2.4.1. Interviewee selection criteria

The right people should be interviewed in order to obtain valuable information. An interviewee is considered suitable if the person meets the criteria and can be classified as an expert in the field. The criteria for selecting an interviewee are as follows:

- The ‘type’ of company or institution the individual works for. The different options are: client, engineering consultancy firm, steel manufacturer, contractor, demolition contractor, and research institutions and firms. The goal is to interview at least $N = 2$ per stakeholder type, with a preference for $N \geq 3$.
- Within these stakeholder types, the aim is to interview individuals in various positions. Positions range from circularity managers with market insight to structural steel engineers. These individuals provide diverse perspectives on steel reuse and its associated challenges, making it valuable to interview a variety of people.
- The interviewee must have at least 5 years of experience working within the supply chain. This

will be selected in advance. To confirm this, an introductory question is asked during the interview, where the interviewee can introduce themselves. Then, they are asked whether they have experience with material reuse and/or specifically steel reuse. This allows the researcher to immediately gauge the interviewee's knowledge on the topic.

In collaboration with experts from Sweco, a selection of potential candidates was created. The interviewees will receive an invitation via email for an interview that will take place in person. If location difficulties arise, the interview will be conducted online instead.

2.4.2. Conducting interviews

In addition to interviewing the right people, the right questions should be asked to obtain valuable information. Therefore, a semi-structured interview format was chosen. This means that a set of questions will be prepared in advance, but there is no strict allocation of time per question. This allows the interviewer to ask follow-up questions when additional relevant information is expected or to seek clarification if necessary. This interview protocol can be found in Appendix J.

Practically, the interviews will proceed as follows. First, the participant will receive the Opening statement, as shown in Appendix H, followed by the Informed consent form in Appendix I. Upon agreement of the consent form, the researcher will begin recording the audio. The interview will be divided into three sections, as outlined in the interview protocol in Appendix J.

- Part 1 of the protocol consists of introductory questions designed to ease into the conversation, in which is focused on general topics like the role of the participant in the company and their professional experience. These questions should also serve as a 'check' to confirm that the interviewee has the necessary knowledge to answer the questions.
- Secondly, the interview will delve deeper into the topic, aiming to gather insights into the identified obstacles. An exploratory open question will be asked first, to avoid leading the interviewee. Afterward, the obstacles found in the literature will be presented, and the participant's views on each of them will be discussed. Additionally, suggestions and strategies will be asked on how to mitigate these obstacles from their area of expertise.
- The final part will include a set of concluding questions. There will be a question about the interviewee's vision for the future, allowing their thoughts to flow freely and giving them the space to think outside the box. The session will end with the question if they have any final thoughts to add, ensuring the session concludes in a pleasant way.

It should be mentioned that the researcher consistently asks follow-up questions. If an interviewee makes a point, the researcher will ask for an 'example' to support the perspective being discussed. This helps substantiate the argument and provides a clearer picture of the point being made.

2.4.3. Sufficient amount of practical data

As described in Section 2.4.1, the goal is to interview at least 3 interviewees per type of stakeholder. This has been predetermined, and it is possible that sufficient information will be gathered earlier or later. Sufficient information is considered to have been collected when no new aspects are revealed by new interviewees. If this is the case, it is acceptable to draw conclusions from the gathered information. If it turns out that all interviewees provide different information, which may even contradict each other, this is also a conclusion, and the conclusion is that there is no consensus.

2.4.4. Effect of selection bias on results

The process of selecting appropriate interviewees, as previously described, is known as 'purposive sampling'. This approach involves deliberately choosing a specific sample set, which creates an intentional bias. This bias is accepted in this thesis, because it is necessary to select knowledgeable candidates to obtain relevant information.

However, when drawing conclusions, this must be kept in mind. People who are enthusiastic about reuse and committed to sustainability are more likely to agree to participate in an interview than those who consider reuse to be unimportant. Therefore, the conclusions drawn from the interviews will apply to a specific subset of the supply chain, namely those individuals who are engaged in reuse. Removing this bias is not attempted in this thesis, and only conclusions about the chosen sample set will be drawn.

2.4.5. Effect of interview order on results

Additionally, the order in which the interviewees are questioned may influence the results. The researcher's knowledge will increase as more interviews are conducted. While the questions will remain the same for each interview, the extent to which relevant follow-up questions are asked may potentially change over time.

Moreover, reuse is a 'hot topic' and current issue. It is a dynamic subject that tends to change. It is possible that during the interviews, there will be new developments, both in terms of policy and technology, that could influence the outcomes of the interviews. A person interviewed later on in the research may enter the interview with different knowledge compared to the first interviewee. This must be taken into account when drawing conclusions from the practical data.

Part I

Literature review on reuse practices by exploring obstacles

3

Principles of reuse

This chapter discusses the various forms of reuse and the goals of the European Commission regarding sustainability. Furthermore, it explains why steel is a relevant material for reuse practices.

3.1. Definition of reuse

The well-known 4R's for reducing environmental impacts are reduce, reuse, recycle, and restore (Cooper and Gutowski, 2017). The term reuse can encompass various forms but generally means giving products or components a second or further use at the end of their initial life without altering their current state. In short, reuse can be summarized as product life extension (Cooper and Gutowski, 2017). In 2019, the European Commission identified the goal of achieving a Circular Economy (CE), which entails preserving the value of materials and resources for as long as possible (Vares et al., 2020). This also means that when a component reaches the end of its lifecycle, efforts should be made to find an alternative application where it can still provide value (Donker, 2021). An overview of this value preservation in circular design is shown in Figure 3.1. In this thesis, reuse depicted within the red section is relevant, referring to value retention through the use of existing materials or more specifically construction components.

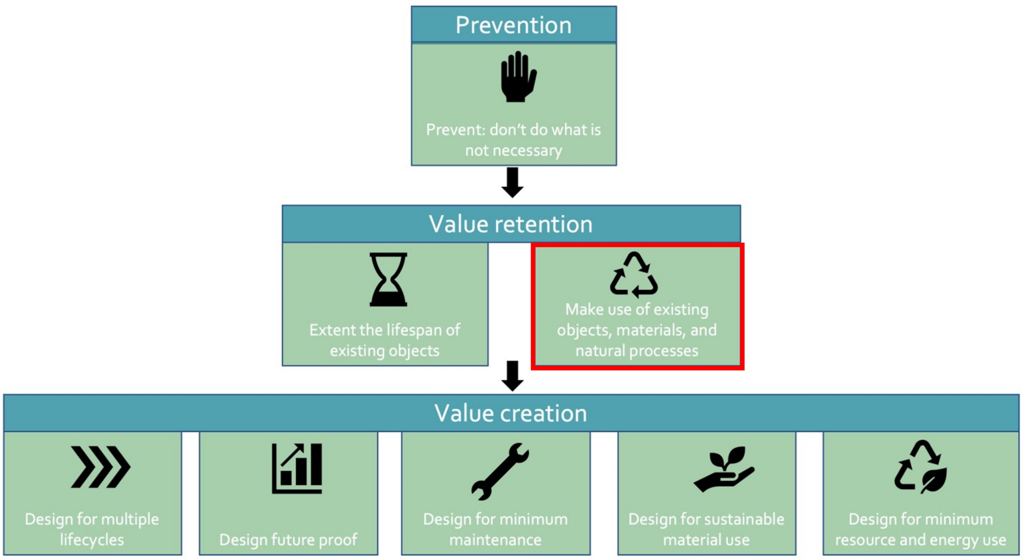


Figure 3.1: Circular design (Donker, 2021).

3.2. Steel and reuse

Steel is considered a material that can be infinitely recycled (García-Peñas and Sharma, 2023). The recycling industry is well-established, and in many parts of the world, highly developed scrap processing systems exist. Approximately 630 million tons of steel are recycled each year (García-Peñas and Sharma, 2023). This is more than the recycling of all glass, paper, and plastic combined, which is why steel is often seen as a permanent material in CE. However, one major drawback is that the melting process required for recycling is very energy-intensive and results in high emissions. Therefore it does not align with the concept of CE. Reuse on the other end, extends the lifecycle of components and therefore supports CE practices of value retention. Life Cycle Assessments (LCA) show that reuse results in significantly lower emissions compared to recycling (Yeung et al., 2017). These advantages are due to two factors: the end-of-life scenario is avoided, and the production of new components is not required (Castellani et al., 2015; Cooper and Gutowski, 2017; Woolridge et al., 2006). As depicted in Figure 3.2, a combination of maximizing reuse as much as possible, complemented by recycling the remainder, is considered optimal in practice (Fivet, 2022).

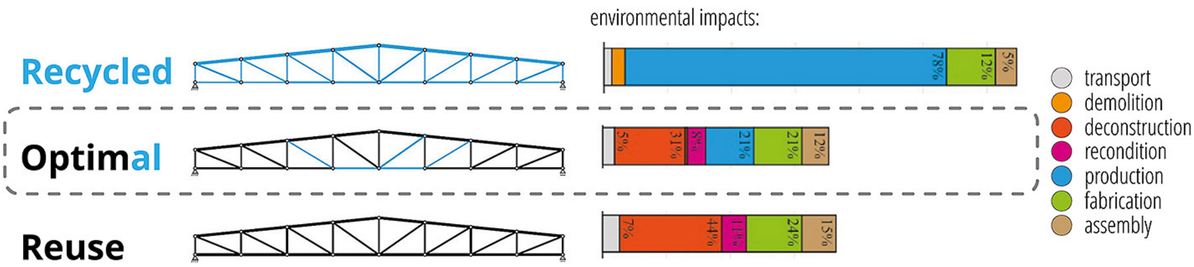


Figure 3.2: Combination of reuse and recycling (Fivet, 2022).

Conclusions

According to the performed literature research the definition of reuse means extending the lifespan of a product. For steel components, postponing new production has the main advantage of reduced emissions, and by extending its life the value of the component is preserved. Since reuse has major benefits, the question remains why it is not yet implemented on broader scale. The obstacles that hinder the adoption of reuse should be explored and this will be done on the basis of a literature research in the next chapter.

4

Obstacles to adoption of reuse

This chapter elaborates on the obstacles that currently hinder the adoption of reuse on the basis of a literature research. The five found obstacles stem from various areas.

4.1. Sourcing of steel

The first step in steel reuse involves identifying steel that will no longer serve its current purpose in the future. This could occur because a site is repurposed (e.g., an office building is demolished) or because a structure can no longer fulfill its intended function (e.g., an obsolete bridge). In both cases, it is essential to assess the current condition of the steel. The material properties of steel are often uncertain, which presents a significant obstacle (Densley Tingley et al., 2017). When the material properties are not properly documented at the beginning of a steel component's lifecycle, determining its residual strength becomes impossible without conducting tests. Therefore, this information must be effectively managed from the start of the component's lifecycle. The information flows between the different stakeholders need to be analyzed to ensure proper management. These flows, along with the material flows, are shown in Figure 4.1. As illustrated, the flow of information about components (or so-called elements) takes place primarily between the fabricator and the stockist. These two stakeholders are the key actors responsible for the data on steel during the early stages of its life (Dunant et al., 2018). They play a critical role in ensuring vertical integration of information within the supply chain to reduce uncertainty regarding steel quality. Vertical integration refers to the arrangement of the supply chain where actors extend their knowledge across subsequent stages of the process.

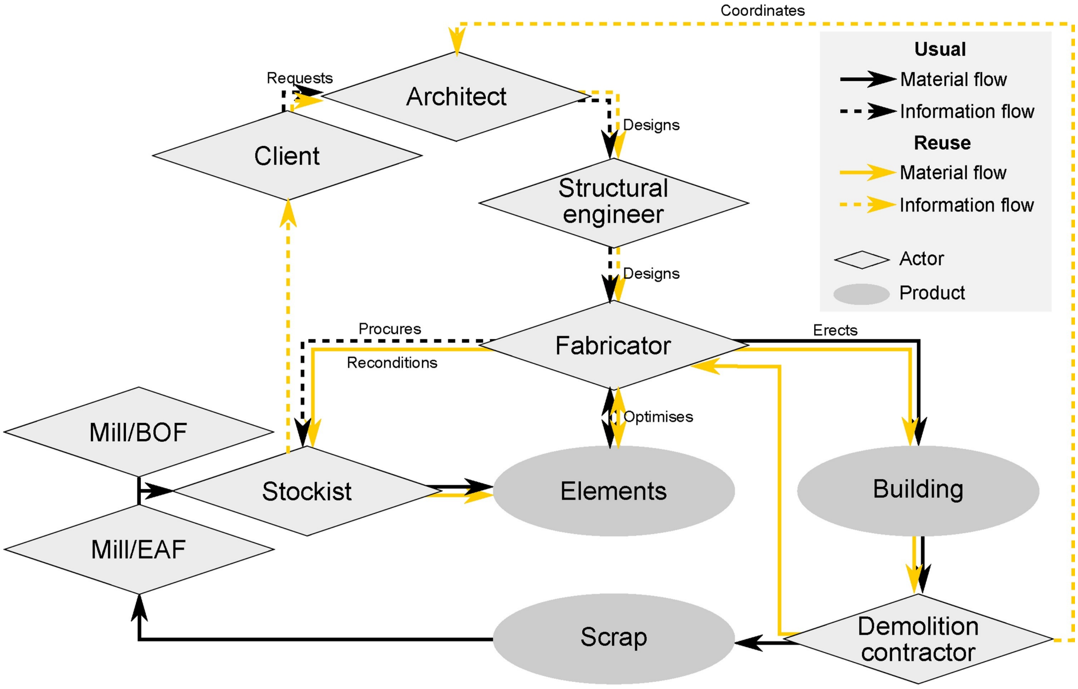


Figure 4.1: Flows between stakeholders (MILL/BOF and MILL/EAF represent two steel-making actors) (Dunant et al., 2018).

In addition to locating the steel, it must also find a suitable place for reuse. These two aspects are interconnected because a component with certain properties may be suitable for one location but not for another. The current condition of the steel and the intended application site are therefore closely linked. In short, a key challenge is finding a new application at the right place and time (Kanyilmaz et al., 2023). During an interview, a contractor described this issue as: “the right steel is available in the right part of the country, when the client wants it, and quick enough” (Densley Tingley et al., 2017). In essence, supply and demand must align for this process to succeed. For stakeholders, it is crucial to eliminate uncertainty in supply. Therefore, a strategy must be developed that outlines what is required from each stakeholder to fulfill their responsibilities in order to reduce uncertainties related to mismatches between supply and demand.

4.2. Re-certification of design standards

For designing with ‘new steel’, numerous NEN standards are available. These standards outline the design requirements to ensure a safe design for load-bearing structures, and these are referred to as Eurocodes (CEN-members, 2002). Together with the Dutch Building Decree, these standards form the foundation of design practices in the Netherlands (Eikelboom et al., 2001). However, as mentioned these standards are intended for new design and not for reused steel. In recent years, a guideline (not a standard) has been developed which is the NTA 8713, which provides support for designing with reused steel from buildings. This marks the first step in establishing guidelines for reused steel. However, for other types of steel, such as sheet piles or steel obtained from the infrastructure sector, no prescribed guidelines currently exist. As a result, these types of steel can not be assessed for safety, and a lack of knowledge exists in this area (Kanyilmaz et al., 2023). This lack of NEN standards presents a barrier for engineers and hinders the implementation of reused steel.

This raises the question of how such standards could be developed. Unfortunately, this is a very complex problem, and significant costs are associated with adapting standards. This immediately results in the involved actors having a reluctant attitude towards change, but this way of thinking will be described further in Chapter 4.5. The immense task of writing new Eurocodes is carried out by hundreds of experts working in committees and groups (Nethercot, 2012). The development of such standards involves collaboration between national standardization bodies, technical committees, and industry experts (Denton et al., 2012). Each committee comprises 250 members, including engineers, researchers, and regulators (Denton et al., 2012). Together, they bring substantial collective expertise to review and improve the codes. Moreover, the process involves several phases, including drafting, enquiry, confirmation by the TC250 secretary and chair, editorial review, feedback round, and finally, a formal vote step before official approval (Denton et al., 2012). In summary, it is an extremely time-consuming and intensive process involving numerous stakeholders, which prevents fast and smooth implementation of reused steel. The lack of standards will need to be addressed by developing new standards, and it is expected that the first steps towards reuse will need to be taken outside existing codes. What is specifically required for each stakeholder to encourage their participation will need to be investigated through interviews.

4.3. Legal frameworks

Once design regulations have been established and reused components comply with them, it is worthwhile to begin marketing them. Issues related to product approval are regulated at the European level (Halonen et al., 2024). Construction products are assessed based on the so-called CE mark, which signifies compliance with relevant EU legislation and enables their sale (Condotta and Zatta, 2021; Kanyilmaz et al., 2023). These standardized marketing conditions are determined by the Construction Products Regulation (CPR) within the European Economic Area (EEA) (Parliament, 2011).

These rules establish a commonly used ‘technical language’ to evaluate construction products based on their performance, creating a consistent approach across the EU (Condotta and Zatta, 2021). This assessment process is schematically illustrated in Figure 4.2. If all required checks are satisfied, the product receives a CE mark. The CE mark not only evaluates the individual performance of a component but also considers its specific application. This is known as a Declaration of Performance (DoP) and is required for construction products to verify whether their application is suitable (Halonen et al., 2024).

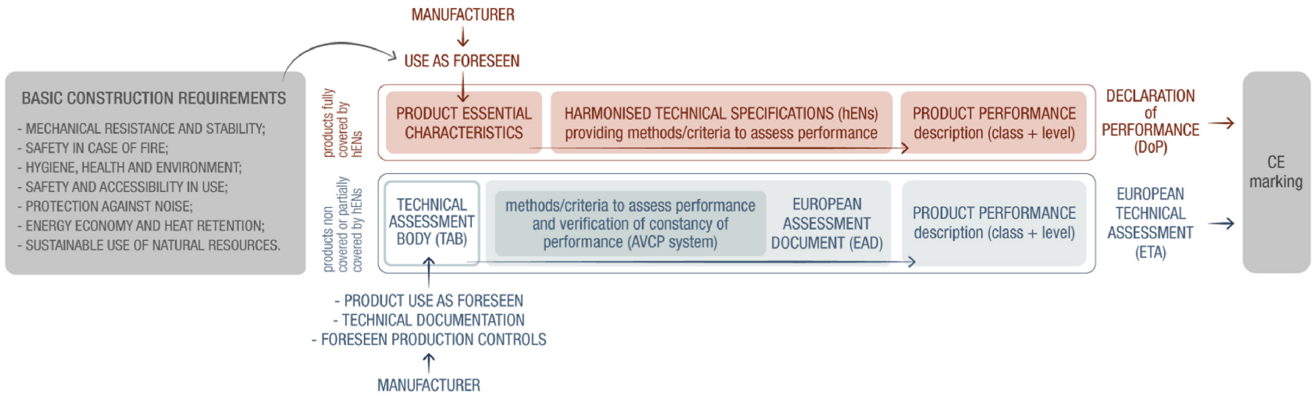


Figure 4.2: Harmonized standards in the EU leading to CE marking (Condotta and Zatta, 2021).

However, there are two key issues with obtaining the CE mark for reused products. First, reused products are already on the market, and the CE mark process applies only to new products entering the market (Halonen et al., 2024). Thus, there is no opportunity for reused products to be granted a CE mark. Second, even if assessment were possible, the existing harmonized standards do not apply to testing the performance of reused components, as these standards are designed solely for performance testing of new production. These gaps in regulations are often referred to as ‘legal vacuums’ and represent a critical obstacle in the implementation of reuse practices (Condotta and Zatta, 2021).

4.4. Costs

In addition to sustainability, one of the main objectives for companies is achieving profitability. Currently, reusing steel is somewhat more expensive than producing new components (Dunant et al., 2018). However, under favorable circumstances, such as the dismantling location being near the reuse site and the components requiring no additional testing, the costs can be lower (Dunant et al., 2018). These potentially increased costs for reuse may hinder the adoption of it. Quantifying the exact cost difference is challenging and uncertain, primarily because the cost of producing a new component is unclear (Cheng et al., 2024). This process involves various stages, from design to erection, involve multiple stakeholders. On the other hand, reuse requires careful deconstruction, which leads to additional labor and storage costs. Storage costs are highly dependent on the location and therefore vary greatly. In short, since it is not easy to determine the profit or loss per stakeholder, and therefore most often remains uncertain, it hinders the adoption of reuse practices.

Moreover, the distribution of profits, costs, and risks is not equitable across the construction industry supply chain (Dunant et al., 2018). In particular, steelwork contractors and stockists will need to undergo significant changes to facilitate the acceptance of steel reuse. For these parties, this represents a risk, and a strategy must be devised to make reuse appealing to them.

A good point to mention is that case studies that are perceived successful often attribute their success to lower costs achieved through reusing practices. This can be observed in an overview of case studies in Figure 4.3, which includes all operations required to deconstruct, store, and reuse per tonne of steel. A few comments on Figure 4.3:

- Guillemont Park was not successful as no buyer could be found for the reused components. This indicates low viability, especially when production costs for new steel are low.
- RHS Hyde Hall was chosen despite the higher costs, likely motivated by a focus on sustainability.

In conclusion, costs play a crucial role in the successful adoption of reuse and in the acceptance of reuse practices by companies.

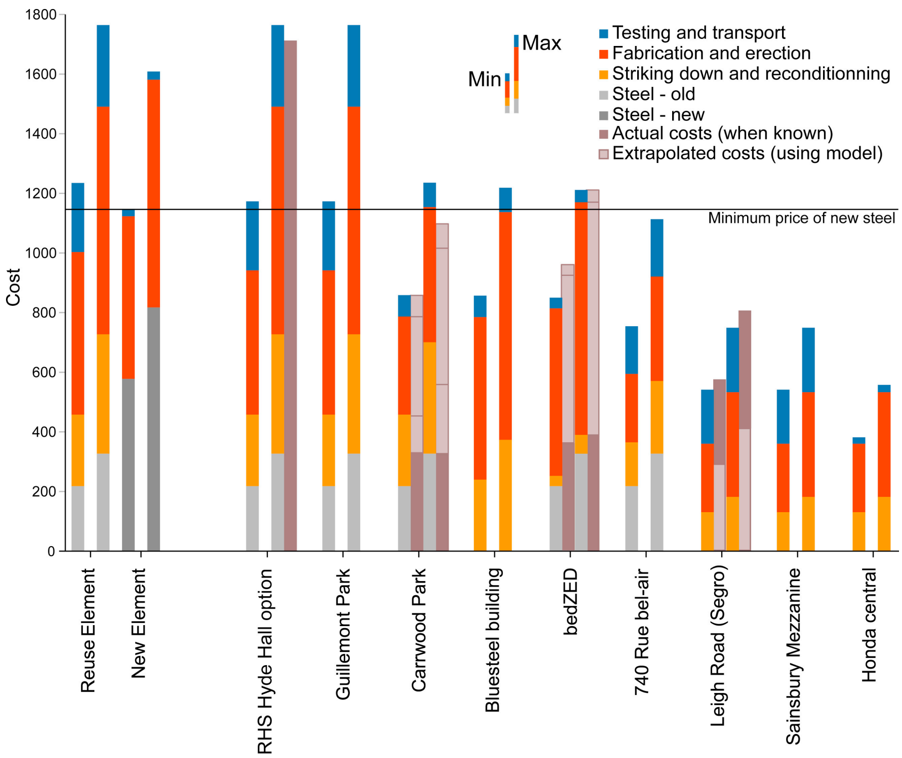


Figure 4.3: Case studies showing operating costs for reusing a tonne of steel compared to producing a new tonne of steel (Dunant et al., 2018).

4.5. Engagement of the construction ecosystem

All the aforementioned obstacles will be closely related to the trust or distrust of all stakeholders in the supply chain. The greater the various uncertainties in quality, availability, and costs, the less eager the construction industry will be to participate in reuse.

Moreover, by nature, the construction sector is not keen on innovation and tends to adopt a resistant attitude (Hart et al., 2019). This is partly because large organizations are unwilling to adapt their way of working, as the linear approach is deeply ingrained. A true shift towards reuse requires flexibility from designers since they will need to design with a limited availability of steel profiles. This circular approach is often expressed through the concept of 'stock dictates design', where design freedom is restricted, requiring innovative engineering solutions.

Additionally, clients must be open and accept the use of reused steel. An interview from literature revealed that a contractor stated: ”some clients would love to do it, but it is too big of a risk to demand it” (Densley Tingley et al., 2017). This has to do with the fact that reused components might not be available on time, causing delays and additional costs. However, it shows that clients are receptive to the idea, which presents opportunities. To change the mindset of the engineers the idea must be embraced and it is crucial to establish a general consensus on the value of reuse to help overcome this obstacle.

Lastly, trust must exist within society, including the users of structures composed of reused components. The uncertainties in quality and design standards can lead to distrust among users. If they lack confidence in second-hand components, this becomes a significant obstacle. This challenge is closely linked to having robust design standards and the ability to ensure safe designs. There is a general consensus about the environmental benefits of reuse, which will positively contribute to the process of acceptance (Tingley and Davison, 2011).

Conclusions

The literature review reveals five obstacles that make the adoption of reuse practices not straightforward. These obstacles stem from various disciplines.

1. Sourcing of the steel is difficult, because sometimes material properties are uncertain. When the properties are known or determined, a suitable place for reuse must be found. A component with certain properties may be suitable for one location but not for another. It must be available at the right place and time, meaning supply and demand must align. ⟶ Material properties (technical) and availability (technical/organizational)
2. There is a lack of design standards. All existing NEN standards focus on designing with new steel. The development of the NTA 8713 guideline supports the reuse of steel from buildings, but for steel profiles from infrastructural structures, a gap remains. ⟶ Assessing structural safety (technical)
   → **This technical issue will be addressed in Part II by ultimately developing a design guideline for assessing the reuse potential of steel bridge components.**
3. There is a lack of regulations within the European Union. Within the EU, products can be marketed if they have a CE mark, but this is currently not possible for reused materials. → EU regulations (regulatory)
4. Costs may currently be higher for reuse compared to new production, and these costs are unevenly distributed across the construction market. Costs are a benchmark for companies and will certainly contribute to the successful adoption or not of reuse practices. → Costs (economic)
5. The adoption of reused components is hindered by the need for engagement from the entire construction ecosystem. The aforementioned obstacles will be closely related to trust or distrust of the supply chain. The chain is risk-averse and tends to adopt a resistant attitude. → Attitudes and perceptions (behavioral/organizational)
   → **To find out whether these obstacles identified in the literature also exist in practice, interviews are conducted with stakeholders. The insights will contribute to the development of a road map that outlines the steps stakeholders should take to enable the adoption of reuse in the supply chain, as described in Part III.**

Part II

Technical reuse potential of steel bridge components

5
Technical background

In this chapter is explained what types of bridges are common in the Netherlands and which components they typically consist of. Then it is elaborated what their strengths and weaknesses regarding reuse are in order to find the most suitable component.

5.1. Bridge typology in the Netherlands

In the Netherlands, bridges are essential for connecting regions and enabling transportation over water. Currently, there are 84,573 registered bridges in the 'Basisregistratie Grootschalige Topografie' (BGT) (Bloksma and Westenberg, 2021). These are spread across the entire country and can be seen in Figure 5.1.

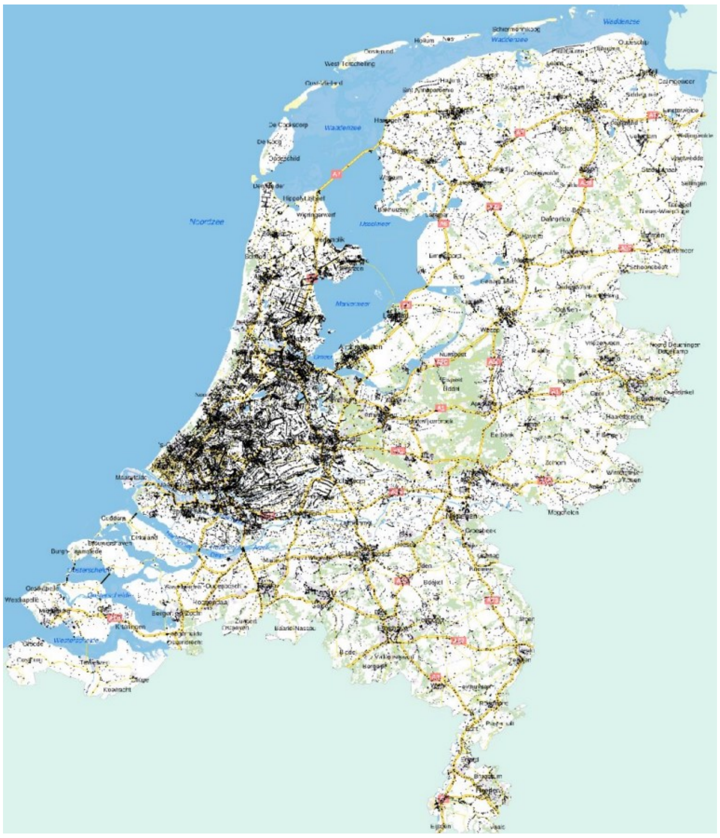


Figure 5.1: Overview of bridge locations in the Netherlands (Bloksma and Westenberg, 2021).

There are several types of steel bridges with different functions, spans and corresponding design considerations. The most common bridges can be divided into five types: beam bridges, truss bridges, arch bridges, suspension bridges, and cable-stayed bridges (Zhang et al., 2022). The characteristics of each bridge type, strengths and weaknesses regarding reuse are summarized in Table 5.1 (Gorgolewski, 2008; Hirt and Lebet, 2013; Kavoura and Veljkovic, 2023; Vergoossen et al., 2023; White, 2015). The various bridge types are schematically visualized in Figure 5.2.

Type of bridge	Typical span [m]	Common components	Strengths regarding reuse	Weaknesses regarding reuse
Beam bridge	[0, 50]	Stiffeners (girders/beams), deck, piers, abutments	Standardized girders can potentially be reused, deck can potentially be reused, straightforward application due to easy structural geometry	Short spans limit adaptability, not aesthetically pleasing
Truss bridge	[10, 300]	Trusses (top/bottom chords, verticals, diagonals), deck, piers, abutments	Modular elements (chords, verticals, and diagonals) can be demounted and therefore potentially reused, deck can potentially be reused	Many connections present which makes disassembly complex, specific geometry limit wide application
Arch bridge	[30, 200]	Arch, suspenders, deck, abutments	Deck can potentially be reused, arch is aesthetically pleasing, bigger spans	Arched components limit wide application or adaptation is required
Suspension bridge	[200, 2000]	Cables (steel strands), suspenders, towers, deck, anchors	Cables and deck can potentially be reused, aesthetically pleasing, bigger spans	Cables have tension-specific requirements which makes reuse hard, anchorages are project-specific
Cable-stayed bridge	[100, 1000]	Stay cables, pylons, deck	Deck and pylons can potentially be reused, aesthetically pleasing, bigger spans	Stay cables are required for geometry so disassembly is complex

Table 5.1: Comparison of bridge types regarding reuse.

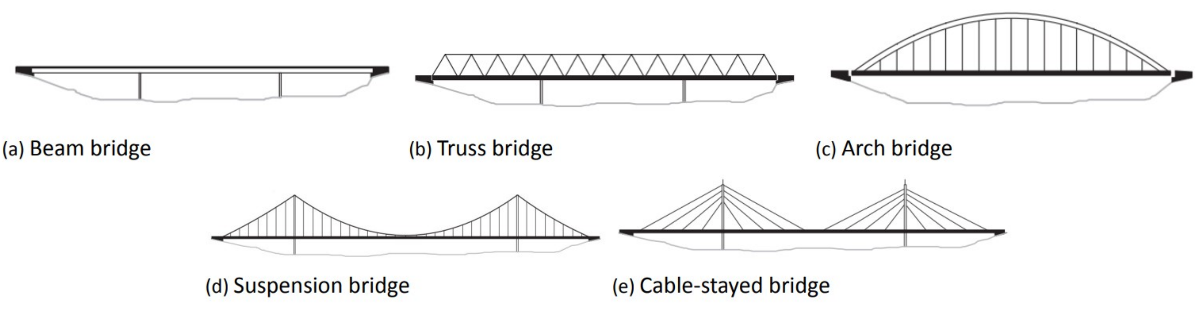


Figure 5.2: Main types of bridges (Hirt and Lebet, 2013).

5.2. Movable bridges

The focus is now shifting to a specific type of bridge. This type is mainly found in smaller spans, usually in regional and provincial bridges, and these are movable bridges. The main reason to choose for a movable bridge instead of a fixed bridge is that the water over which the bridge spans does not lose its function as a waterway. Each of the five previously mentioned bridge types can be built in combination with movable spans (the least common being movable suspension and cable-stayed bridges, but this is still possible as seen with the Tower Bridge in London) (Koglin, 2003). The three most common movable mechanisms are swing, bascule, and vertical lift bridges. The difference between these three is that a swing bridge opens by pivoting about a vertical axis, thus rotating. A bascule bridge pivots about a horizontal axis and has a counterweight. Vertical lift bridges open by lifting without rotating or translating in the horizontal direction (Koglin, 2003).

Type of bridge	Typical span [m]	Common components	Strengths regarding reuse	Weaknesses regarding reuse
Swing bridge	[20, 100]	Swing mechanism, deck, piers, bearings	Deck can be reused, mechanism can be disassembled and reused in some cases	Swing mechanism is complex and specific to the project, disassembly and reassembly can be difficult due to specific geometry
Bascule bridge	[20, 150]	Movable span (leafs), counterweights, piers, deck, bearings	Counterweights and deck can be reused, parts of the movable span may be reusable	Bascule mechanism is complex and specific to the project, disassembly and reassembly can be difficult due to specific geometry
Vertical lift bridge	[20, 200]	Lift span, towers, lifting mechanism, deck, counterweights, piers	Deck, counterweights and towers can be reused, lifting mechanism may be reusable in some cases	Lifting mechanism is project-specific, disassembly and reassembly can be difficult due to specific geometry

Table 5.2: Comparison of movable bridges regarding reuse.

Based on Tables 5.1 and 5.2, it can be concluded that the reuse potential is high for the deck and counterweights. For all types of bridges, the deck offers possibilities for reuse. An example of such a deck is shown in Figure 5.3 and is referred to as an Orthotropic Steel Deck (OSD). The term ‘Ortho’ refers to the orthogonality of the deck, while ‘Tropic’ highlights its anisotropic nature, these two combined resulting in the fact that it has different properties in both directions (Kolstein, 2007). The top component of the OSD consists of a slender steel plate supported by a set of longitudinal ribs (Connor, 2012). Beneath these ribs are transverse beams, which are further supported by main girders. The OSD (comprising the various parts) is therefore a suitable component for further analysis for reuse.

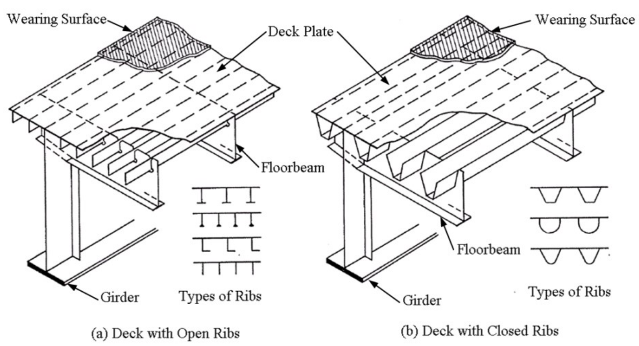


Figure 5.3: Components of Orthotropic Steel Deck (Connor, 2012).

5.3. Selection of OSD as suitable component for reuse

In Section 5.2 OSDs have been chosen for further analysis regarding reuse. These types of decks are high-value components because they can carry a relatively high load compared to their weight. They are labor-intensive to produce, because of all the welds and therefore it is beneficial to utilize them for as long as possible instead of melting them down.

Additionally, with regular maintenance, the decks often have not yet reached the end of their lifespan and can still serve their function. If they have reached the end of their lifespan, there is a lot of knowledge about damage patterns and the necessary repairs related to OSDs that can be carried out to enable reuse. It is common to assemble the deck into a so-called ‘module’ with maximum dimensions to be able to transport it to the desired location. It must be figured out when it is more favorable to reuse it as a whole or split it up into sub-components (slender deck plate, cross beams, and girders).

→ **By first zooming out to examine the general bridge types throughout the Netherlands, and then narrowing the focus to different types of movable bridges, it emerges that the deck is chosen to assess further for reuse potential**. An OSD can either be reused as a whole in a second life or dismantled into its sub-components (slender deck plate, cross beams, and girders). These individual sub-components are also suitable for various reuse applications. To determine the suitable and possible applications, the current condition of the respective component must be assessed. In other words, the damage sustained during its first life must be understood in order to calculate the expected remaining lifespan.

5.4. Steel in its previous life

Since in this thesis it is about steel reusing instead of recycling, the steel has by definition already had a first life. For this reason, the steel may have sustained some damage during its first life. Therefore, it is crucial to perform an analysis of the ways steel can fail to better understand and identify the damage. In general, steel fails when the applied stress exceeds the material’s strength (McEvily and Kasivitamnuay, 2013). A schematic representation of this is shown in Figure 5.4. For reused steel, the applied stress in its first life will have never exceed the material’s strength. Otherwise, it would have already failed, leaving no possibility for a second life. Although this concept forms the basis of steel failure, there are many ways in which it can fail. To accurately predict the behavior of steel, a distinction is made between most common failure mechanisms. This provides a broader understanding of the existing damage in the steel and makes it possible to determine whether a particular reuse application is feasible and viable.

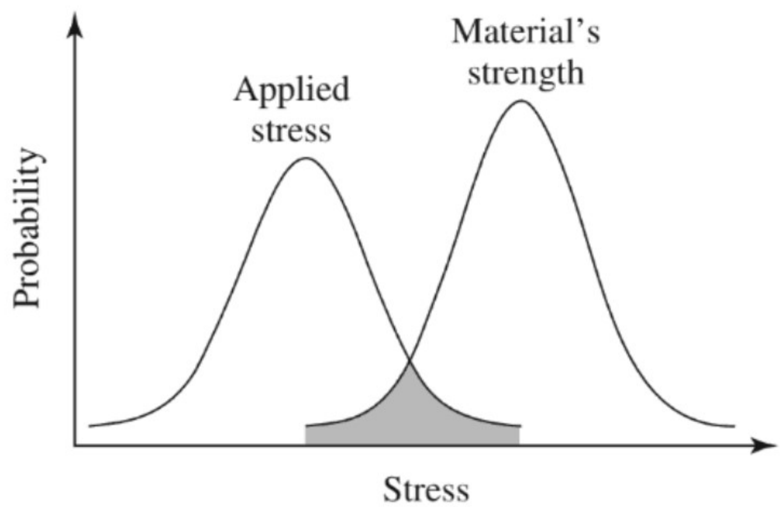


Figure 5.4: Schematization of frequency distribution of applied stresses and the material’s resistance (McEvily and Kasivitamnuay, 2013).

5.5. Fracture types

There are different ways in which the fracture of steel can appear. The two most basic ways are called brittle and ductile fracture, and they are distinguished based on the speed of occurrence (Farhat, 2021). Brittle fracture is more common under static loading, while ductile fracture occurs more often at a slow rate. How these types of fractures occur is explained in more detail below for each type.

5.5.1. Ductile fracture

Ductile fracture is a mode where the elastic limit of the steel component is exceeded, causing the material to reach the so-called ‘plastic zone’ (Pineau et al., 2016). The steel component will undergo plastic and thus permanent deformation (stretching or bending) until it reaches the ultimate tensile strength (Craig, 2005). The deformation of the component will vary but can be recognized by a local thinning of the cross section, as can be seen in Figure 5.5. The stretching process occurs because so-called ‘cavities’ in the steel continue to grow (Benzerga and Leblond, 2010). If this process continues until the maximum load is reached, local necking will occur, meaning that the material’s strain hardening can no longer compensate for the reduction in the load-bearing section due to plastic deformation (Berdin et al., 2004). Eventually, the already deformed and stretched specimen will break into two pieces, as shown in Figure 5.5.

5.5.2. Brittle fracture

On the other hand, brittle fracture occurs at stresses below the yield strength (Berdin et al., 2004). Brittle fracture, as the name suggests, involves no deformation and therefore will happen suddenly (Craig, 2005). It occurs as a sudden accident and there will be no warning from the material that a fracture is going to occur. Brittle fracture is also known as the process of ‘cleavage’, and can happen at different locations such as welding defects, fatigue cracks, or inclusions (Smith, 1968). Brittle fractured components will have flat fracture surfaces, as no plastic deformation will occur since the component does not reach the plastic zone (Pineau et al., 2016). The cause of brittle fracture is often high local stress, such as can be seen at welds. Furthermore, higher local internal stresses can be observed in thicker components than in thinner ones, because larger grain sizes are used in the production of thick steel, and there is a higher chance of temperature differences between the center and the ends (Berdin et al., 2004).

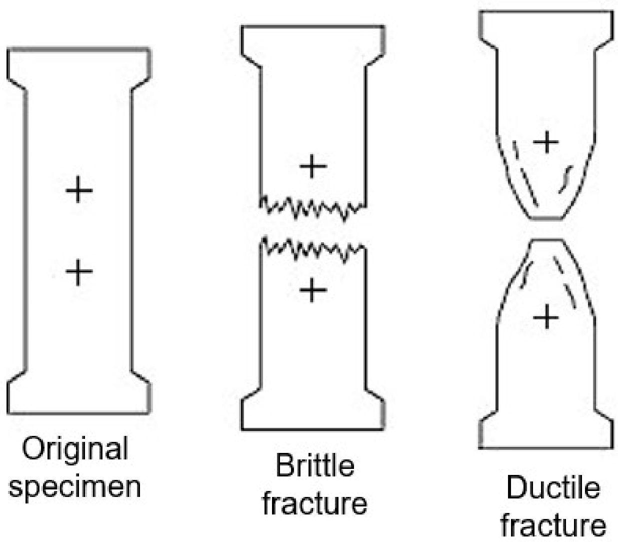


Figure 5.5: Schematization of brittle and ductile failure.

5.6. Failure modes

The occurrence of one of the types of fractures is caused by a (combination of) failure mode(s). A distinction is made between the most common types of failure modes for steel, namely fatigue, corrosion, creep, and buckling. These failure modes will be explained in depth from a more materials science point of view. This will help in understanding the behavior of steel better, and with this knowledge, a more structural engineering approach can be applied in order to determine the governing mechanisms that should be considered when assessing the reuse potential of steel.

5.6.1. Fatigue

Fatigue plays a major role in the damage of metallic structures and is even stated to be the most prominent failure mechanism in steel components (Mittemeijer, 2010; Rege and Lemu, 2017). The phenomenon of fatigue can be described as the progressive degradation of a component caused by fluctuating stress over an extended duration of time (Schijve, 2003). These repetitive stress cycles can either be the result of cyclic loading (cyclic fatigue) mostly due to traffic, a constant load (static fatigue) or an arbitrary load (Mittemeijer, 2010).

The nominal stress resulting from this loading has a maximum value that is considerably lower than the maximum tensile stress of the steel structural member (Guijt, 2023). At each cycle, a small plastic deformation will occur, and after many cycles this will eventually lead to failure of the component. A distinction is made between two phases. The first is the crack initiation phase, followed by the crack propagation phase, during which the crack continues to grow over time (Schijve, 2003). At weld locations, there are several reasons why the likelihood of fatigue cracks is higher. First, welding creates initial defects and imperfections such as notches and pores (Fuštar et al., 2018). In addition, welds cause a sudden change in the geometry of the component, leading to high local stresses, as shown in Figure 5.6 (Hageman, 2022). Finally, during the welding process, the material is rapidly heated and then cooled, resulting in residual stresses at the ends of the weld.

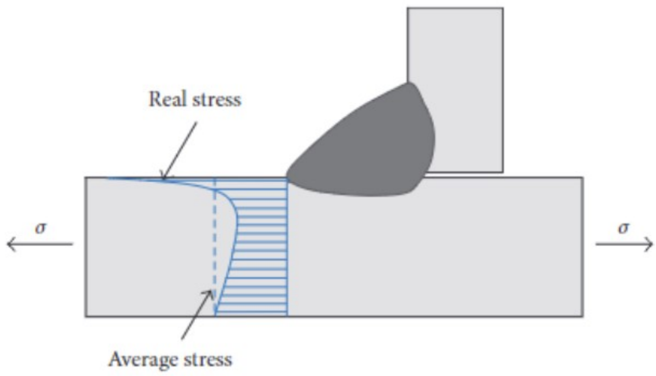
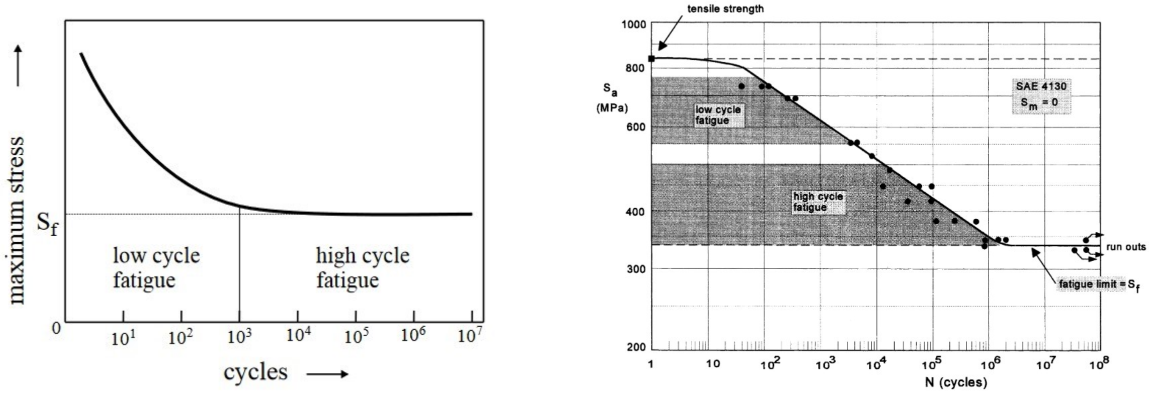


Figure 5.6: High local stresses at weld (Fuštar et al., 2018).

The formation of cracks in metallic members is the result of tensile forces, compressive forces counteract crack formation (Mittemeijer, 2010). The maximum tensile stress that can be applied is expressed by the parameter 'S'. In combination with the parameter 'N', which represents the number of cycles to failure (with varying amplitudes), the phenomenon of fatigue is presented in 'S-N' curves. These curves are also known as Wöhler curves and a schematic example of this can be seen in Figure 5.6. The general trend shows that at a relatively high value of maximum tensile stress (S), failure of the specimen occurs after a relatively low number of cycles (N). This is also referred to as low-cycle fatigue. The point S_f indicates the endurance limit, meaning that the fatigue limit has been reached, and no failure will occur regardless of the number of cycles. The determination of such values is done empirically in laboratory tests, where a specimen is subjected to alternating loading below the yield limit of the tested steel, usually with a constant amplitude. Multiple tests are conducted, from which the number of load cycles until failure and the magnitude of the alternating loading stress are obtained. A line can be fitted through the various data points, resulting in a smooth S-N curve as shown in Figure 5.7a.



(a) Schematic Wöhler curve (Mittemeijer, 2010) **(b)** Fatigue test results (Hageman, 2022).

Figure 5.7: S-N curves.

In the Eurocode S-N graphs are presented on a log-log scale, as shown in Figure 5.8 (CEN-members, 2012c). The fatigue design life is at 2×10^6 cycles. Furthermore, the algebraic expression in Equation 5.1 describes the number of cycles until failure (N) as a function of the stress range ($\Delta\sigma$), with intersect parameter (a) and inverse slope parameter (m). With this expression, the fatigue resistance of a specimen can be determined. The uncertainty regarding the scatter presented in Figure 5.7b is taken away by incorporating a safety margin of 2.3% exceedance (Hageman, 2022). In this way, S-N curves can serve as a practical method in the assessment of fatigue loading and the corresponding fatigue damage.

$$N(\Delta\sigma) = \frac{a}{\Delta\sigma^m} \tag{5.1}$$

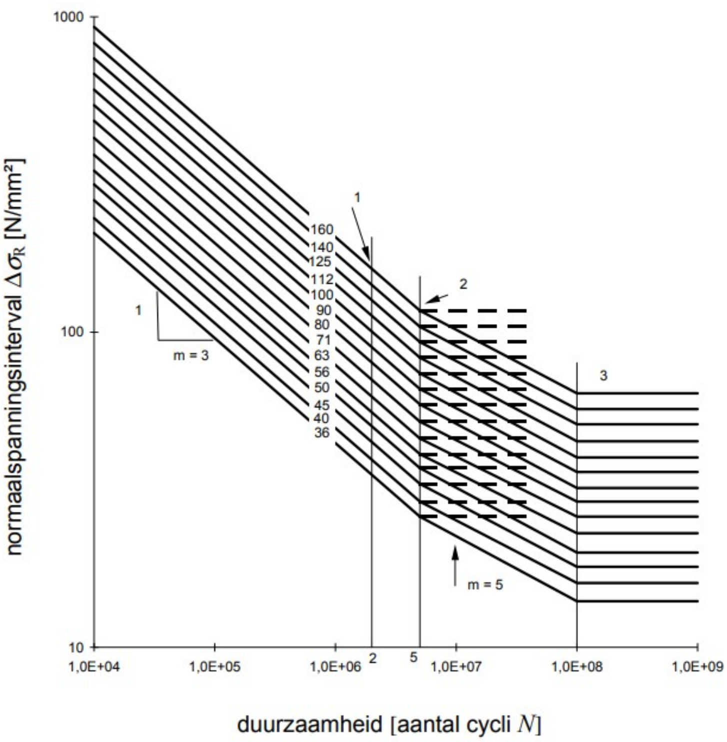


Figure 5.8: Fatigue curves for different stress ranges; 1 indicates the normal stress at 2 million cycles, 2 represents the fatigue limit at constant amplitude ($\Delta\sigma$) and 3 describes the endurance limit (CEN-members, 2012c).

5.6.2. Corrosion

Another major failure mechanism in steel structures is corrosion. This involves an electrochemical process in which oxygen deteriorates the outer layer of the steel (Craig, 2006; Tullmin and Roberge, 1995). The alternation between wet and dry environments increases the likelihood of corrosion, because the electrolyte layer on the outside of the steel is diluted, which allows oxygen to pass through more easily (Kolesar, 1974). Furthermore, temperature, relative humidity, atmospheric pollutants, and salinity play a crucial role in the rate of corrosion (Imam, 2019). Corrosion is visible to the naked eye through the formation of a rust layer. However, beneath this layer, there are often invisible so-called ‘pits’ (Khoshnaw and Gubner, 2020). These are small cavities beneath the surface, as shown in Figure 5.9. These pits are very dangerous because they are not visible and can grow into large cracks.

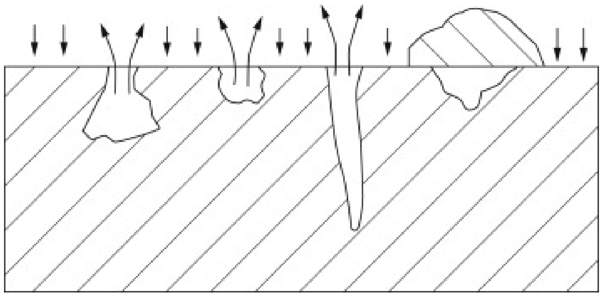


Figure 5.9: Pitting corrosion (Khoshnaw and Gubner, 2020).

Failure will ultimately occur if thinning of the cross section continues, as the resistance decreases. The estimation of corrosion loss can be done according Formula 5.2 (Imam, 2019).

$$C(t) = At^B \tag{5.2}$$

where $C(t)$ is the average loss of thickness after t years of corrosion (coefficients A and B can be found through experiments).

Not all parts of a steel structure will be equally susceptible to corrosion. Figure 5.10 shows which components of a steel bridge are susceptible to corrosion.

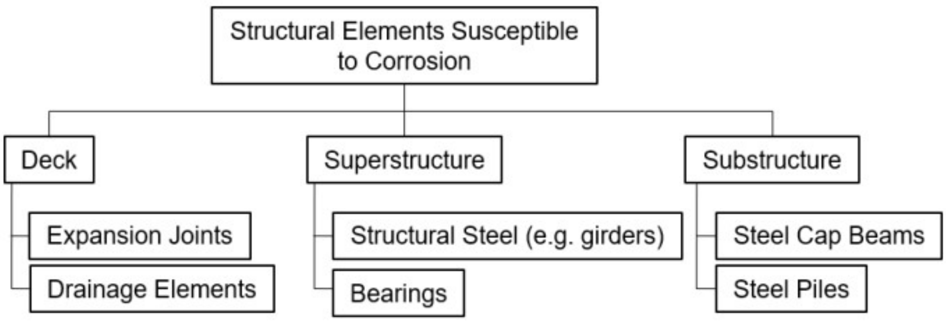


Figure 5.10: Steel components susceptible to corrosion (Board et al., 2013).

There will be areas in the deck that are uniformly and completely affected by corrosion. However, corrosion can also take the form of localized deterioration, which applies specifically to certain areas of a profile. Localized reduction can lead to higher stress peaks and a local decrease in strength. It is necessary to assess whether such a peak affects the behavior of the bridge (Board et al., 2013).

An example of this can be seen in Figure 5.10, where water has seeped through cracks in the deck plate, causing water to accumulate underneath and leading to corrosion. In general, it can be stated that if an unintended water flow occurs, that area is likely to be susceptible to corrosion.

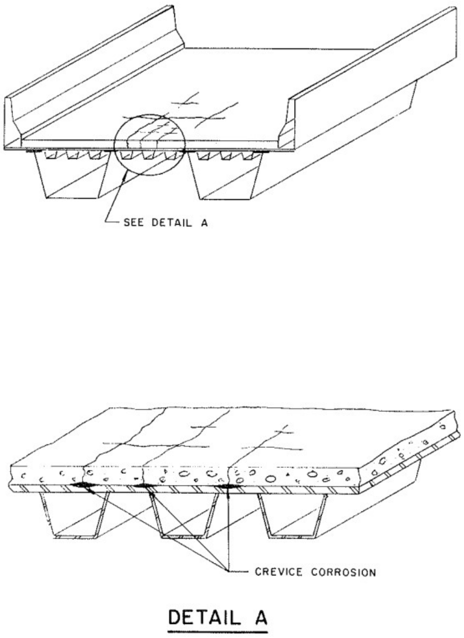


Figure 5.11: Corrosion prone detail of OSD (Kulicki and National Research Council (U.S.), 1990).

5.6.3. Creep

Creep is a time-dependent failure mechanism and also depends on temperature and the applied load (Craig, 2005). In Figure 5.12 are the three different phases (primary, secondary and tertiary creep stage) shown and these are respectively related to the decrease, the constant and the increase of the creep strain rate (Penny and Marriott, 2012). Steel will deform inelastically at high temperatures, even if the stress is well below the yield strength. This deformation of the geometry can continue to the point where the component is no longer able to perform its original function, resulting in creep failure. In extreme cases, this can even lead to a fracture. However, without high temperatures, creep does not occur much, so as long as there is no fire at the structure this is not a common failure mode.

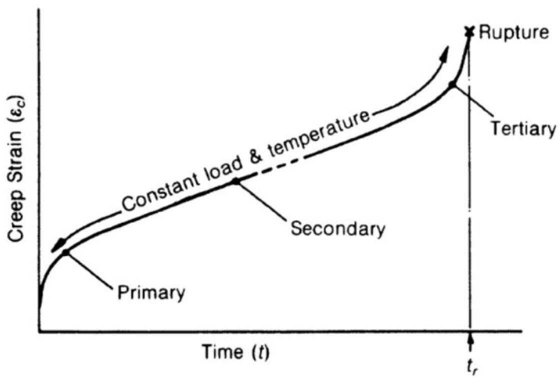


Figure 5.12: Creep strain rate in standard creep test (Penny and Marriott, 2012).

5.6.4. Buckling

The next failure mode is buckling, which is related to the geometry of the component and the geometry of the rest of the structure (Eslami et al., 2018). It is caused by a compressive force, as is depicted in Figure 5.13, in contrast to the other described failure modes that are results of tensile forces. Buckling typically occurs in slender components such as columns or plates with a small thickness relative to their length (Jones, 2006). This failure mode is not commonly found in bridges, but can be observed in, for example, the vertical members of trusses or the horizontal plates of the deck.

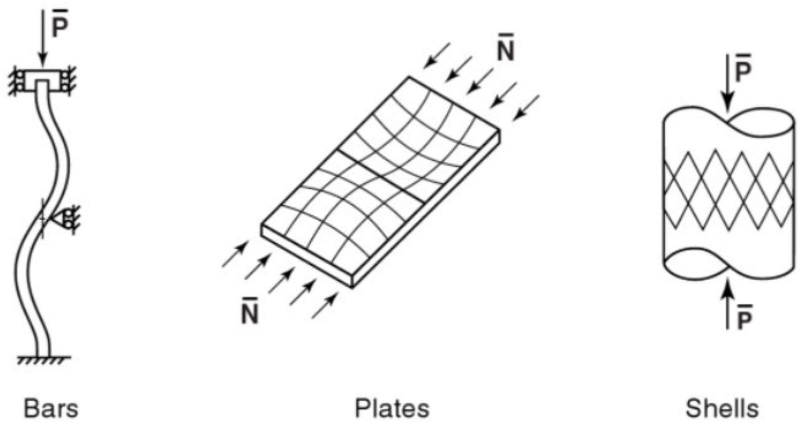


Figure 5.13: Buckling of structural components (Jones, 2006).

5.7. Governing modes

Now that the basic failure mechanisms for steel are understood, a decision can be made on which of these are relevant for determining the reuse potential of a steel component. All can potentially contribute to failure, but to simplify and accelerate the assessment of reuse potential, a selection is made of the most governing modes.

- **Fatigue** should be taken into consideration. It is the most common failure mechanism for metals subjected to cyclic loading. This will always be relevant in case of reusing steel bridge components. The extent of fatigue cracks depends on the stress history and, therefore, the loading history of the bridge needs to be calculated or known.
- **Corrosion** failure is advised to be considered during the assessment of reuse. When inspecting components for reuse, the current condition of the component is recorded. It is impossible to state that no corrosion is allowed since structures are exposed to outdoor conditions. Therefore, an estimation of corrosion damage can be established based on ISO-9224-2012. A prediction for corrosion degradation in the future can be made and the component can in this way be designed slightly over-dimensioned. If further corrosion occurs, it is not problematic because there is still excessive cross section remaining.
- **Creep** is expected not to contribute to failure because, without high temperatures, creep rarely occurs and is therefore not considered critical in general situations.
- **Buckling** failure is expected not to occur. This will only happen due to compressive forces in slender structures, which is uncommon in horizontal bridge components.

Combination of modes

For the practical application of corrosion and fatigue in a specific situation, the combination of both should also be considered. Due to the synergistic combination of both, the damage can be greater than the contributions of both mechanisms working separately. This is also called Corrosion-Fatigue (CF) damage and occurs especially in aluminum alloys, carbon and stainless steels, or in other words, in structural steels (Larrosa et al., 2018). CF damage is a self-reinforcing degradation process. There exist two ways in which both mechanisms have mutual interaction with each other, namely:

- Due to corrosion a reduction of the cross section will occur, which results in a reduced resistance.

These local stress amplifications can lead to more fatigue cracking. Besides to that, the fatigue strength of corrosion products is much lower than steel (Milone and Landolfo, 2022).

- Due to environmental conditions the development of corrosion pits occurs, and these pits can serve as initiation points for fatigue cracks, meaning the pits act as a kind of trigger (Rokhlin et al., 1999). In turn, fatigue cracks can accelerate the growth of corrosion pits as the protective layer of the steel will be damaged.

So the two mechanisms reinforce each other and this should be taken into account in the assessment for reuse. The combined effect is shown in Figure 5.14. It can be seen that in a corrosive environment, there exists no endurance limit. The curve never becomes horizontal, which means that the steel will always fail when subjected to enough cycles. For designing, this means that prescribing a certain amount of allowed cycles at a certain stress is required.

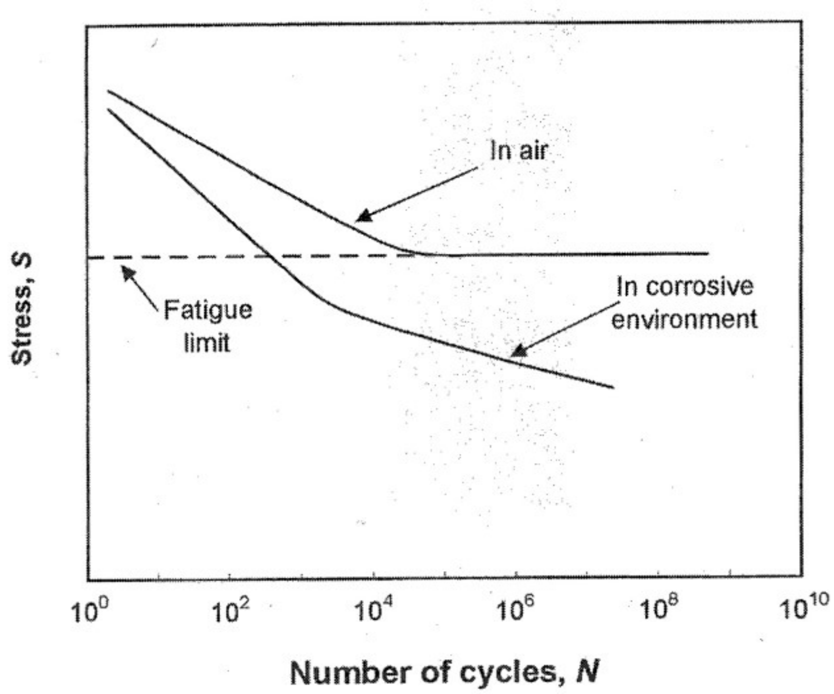


Figure 5.14: Combined effect of fatigue and corrosion (Shipilov, 2005).

Conclusions

In short, the assessment for reuse must include several failure mechanisms to understand the behavior of the steel. The loading history must be calculated to determine any potential fatigue damage. Additionally, a check for corrosion damage and prediction must be present. Lastly, the combination of these two mechanisms should be taken into consideration. In the next chapter is explained how these checks can be practically taken into account, by describing the steps that need to be followed to determine the reuse of steel bridge components.

6
Case study

This chapter presents some general information about the bridge case which is chosen to analyse and explains why it is relevant. Furthermore, some images from the location and the bridge itself are provided.

6.1. Bridges in municipality of Pekela

In and around the municipality of Pekela, there are about 30 bridges in need of 'replacement and/or renovation'. An overview of these bridges, categorized into families, can be seen in Table 6.1. One bridge is chosen to specifically analyze as a case study.

Family	Amount	Type of bridge	Bridges	Characteristics
1	3	Bascule bridge steel	Hekbadde, Zuidkantklap, Eendrachtsklap	Lattice balance beam, very slender construction, cylindrical counterweight
2	2	Bascule bridge steel	Freebrug, Koenemanbrug	Traffic bridges, kink in tower legs
3	1	Bascule bridge steel	Blijhamsterbrug	Straight tower legs, control building
4	2	Bascule bridge steel	Unionbrug, Ericabrug	Open tower legs
5	1	Bascule bridge wood	Albionbrug	Wooden bridge
6	4	Swing bridge, stays	Dekbadde, Giekbadde, Roefbadde, Samenwerkingsdraai	Swing bridge on concrete slab foundation and portal with stays. Manual operation
7	3	Swing bridge, stays	Bronsveendraai, Lubbemansdraai, Hanekampsdraai	Swing bridge on masonry pier, portal with decorative arch and stays
8	3	Swing bridge over sluice gates	Boegbasse, Roerbadde, Kielbadde	Narrow near sluices, operation with cams and pivot point on lock wall
9	1	Swing bridge, stays	Tildraai	Swing bridge on concrete pier and pylons with stays
10	4	Swing bridge	Bakkersdraai, Schooldraai, Koloniedraai, Zuiderdraai	Swing bridge on masonry pier, wooden deck, operation with cams
11	1	Swing bridge	Camphuisdraai	Concrete pier with steel rail track, operation with wheels
12	1	Swing bridge	Verlaatjesdraai	Swing bridge with wooden foundation piles under main pivot point

Table 6.1: Overview of bridges that need renewal around Pekela obtained from the dossier of Sweco.

6.2. Location of Freebrug

The chosen case study bridge is called 'Freebrug', and is located in Oude Pekela, as shown in Figure 6.1. The bridge connects residential areas around Pekela and spans the Pekelerhoofddiep. In this specific region of the Netherlands, approximately 30 similar bridges can be found. These bridges are all due for renewal, making this a significant issue in the area. This specific type of bridge is common in the Netherlands also beyond this certain region (Maps, 2024). Therefore this case study serves as an important investigation, and knowledge about reusing components from these bridges is widely applicable. Additionally, the bridge in Oude Pekela includes an OSD, which is as demonstrated in Chapter 5, an interesting component for reuse. OSDs are often used in movable bridges, because they have a relatively low weight compared to reinforced concrete deck slabs (Chavel, 2012). This lower weight reduces the power required for movement and decreases the need for counterweights.

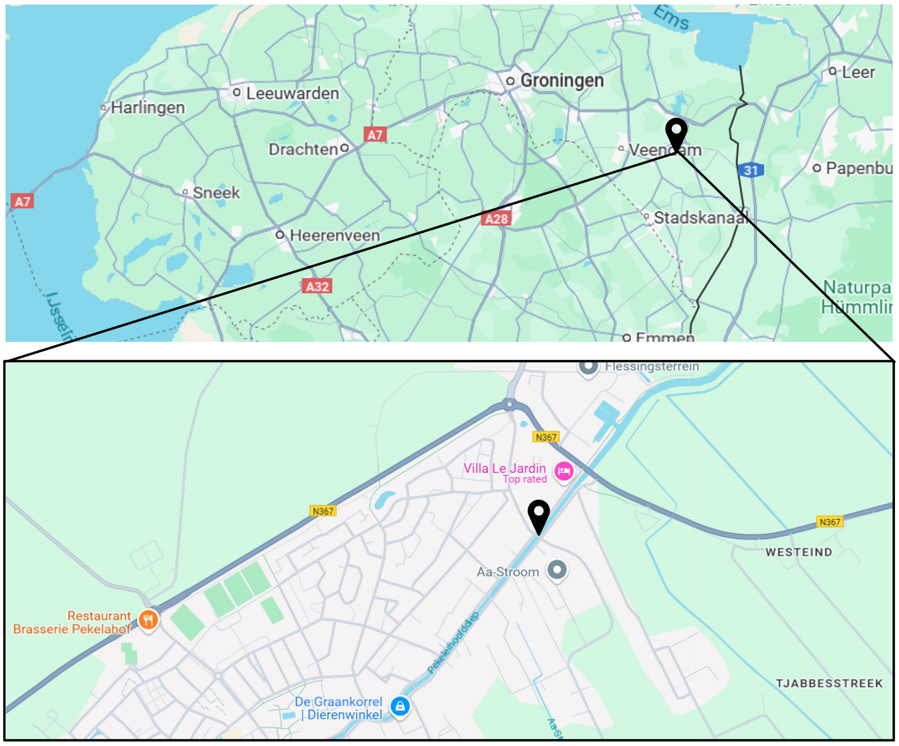


Figure 6.1: Location of bridge (Maps, 2024).

Furthermore, the bascule bridge has two traffic directions and is designed for pedestrians, cyclists, cars, and trucks (Maps, 2024). A front view and side view of the bridge can be seen in Figure 6.2. Its span is relatively small, making it a suitable initial step for introducing and testing the reuse of components. Additionally, the shorter span offers greater creative freedom in structural design, allowing easier adaptation to a random set of components (van Lookeren Campagne, 2022).

(a) Front view Freebrug (Maps, 2024).

(b) Side view Freebrug (Maps, 2024).

Figure 6.2: Snapshots Freebrug.

7

Model

This chapter explains how the model is created in SCIA Engineer. It also provides a detailed explanation of the applied loads and load combinations. Finally, the model is run, and critical areas are identified based on the stresses found.

7.1. Component information

The Freebrug is a steel bascule bridge with an OSD. As described in Section 5.3 the OSD is selected as a component to assess for reuse. The deck of the Freebrug consists of two primary girders with four secondary girders in between. On these girders, an deck plate with troughs is present. According to the available drawings, the steel is made from S235, and the data can be seen in Table 7.1.

Quantity	Type	Dimensions	Material
2	Main girder	HE 700 A x 8775	St37-2*
2	Hinge plate	635 x 40 x 1000	St37-2*
1	Deck panel	7675 x 5994 x 15	St37-2*
4	Cross beam (upper plate)	350 x 16 x 5994	St37-2*
8	Cross beam (combined U - profile)	715 x 16 x 6883	St37-2*
44	Trough (little parts within cross beam)	550 x 5 x 268	St37-2*
11	Trough (near hinged support)	590 x 5 x 1796	St37-2*
22	Trough (near sliding support)	590 x 5 x 2296	St37-2*

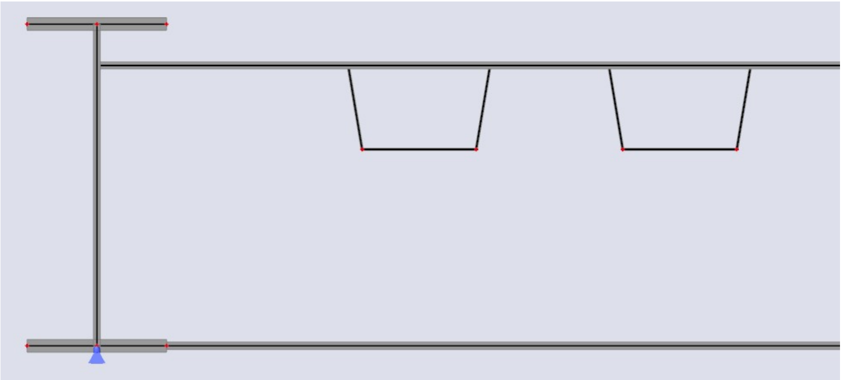
Table 7.1: Overview of structural components based on dossier from Sweco.

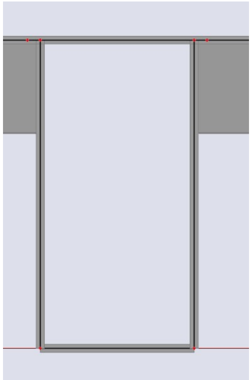
**Steel grade ST37-2 is a German designation for S235.*

7.2. Building the model from plates

The building of the model in SCIA Engineer 24.0 can now begin, based on the drawings from the dossier provided by Sweco. The main girders and troughs are shown in Figure 7.1a, while the cross beams are shown in Figure 7.1b.

Each of these beams/girders is made of ‘plate material’, which refers to 2D plates in SCIA Engineer. By connecting the plates at the joint point, also called a ‘node’, a rigid connection is created to simulate the weld. Although a weld is not completely rigid, this assumption is made and further explained in Section 9.2. The troughs are modeled at the angle according to the drawings, and the deck is placed on top of the cross beams as is shown in the drawings.





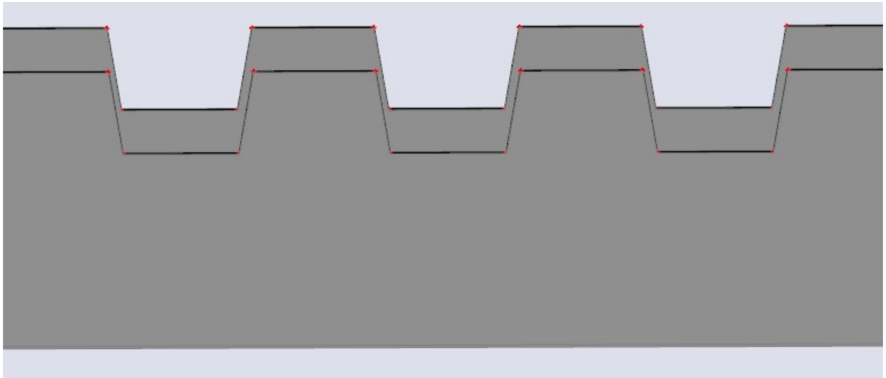
(a) Main girder and troughs in SCIA Engineer.

(b) Cross beam in SCIA Engineer.

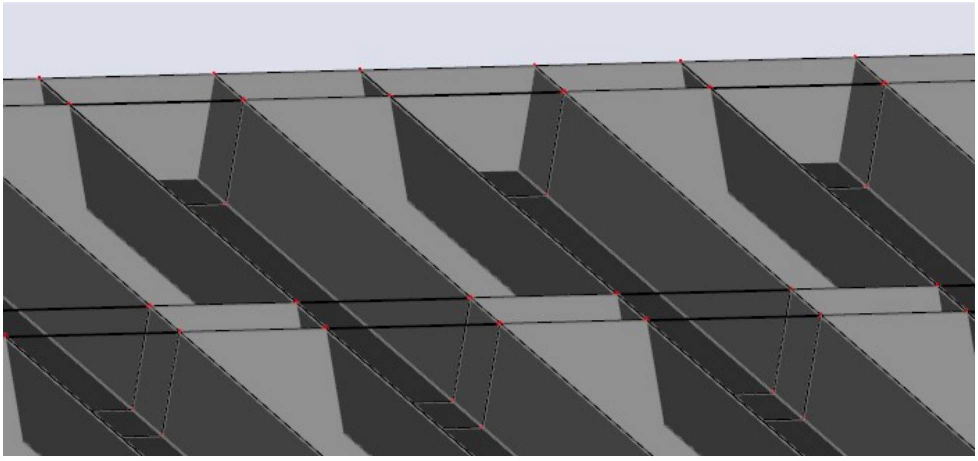
Figure 7.1: Main girder, troughs, and cross beams in SCIA Engineer.

Two types of models

To obtain a more general design for an OSD so that the results are more widely applicable, two types of troughs have been modeled. A distinction is made between continuous and discontinuous troughs. Discontinuous means that no cut-out hole is present in the cross beams, and the troughs stop at the point where they encounter the cross beam, as shown in Figure 7.1b. However, due to the fact that modern laser machines can easily cut steel profiles, continuous troughs are increasingly used, where a cut-out hole is made in the cross-beam. This is illustrated in Figure 7.2a and 7.2b.



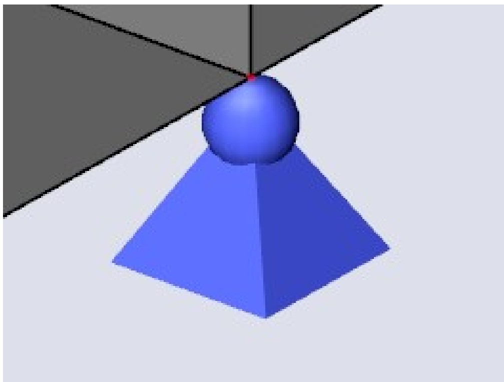
(a) Side view of cut-out holes in cross beams without troughs.



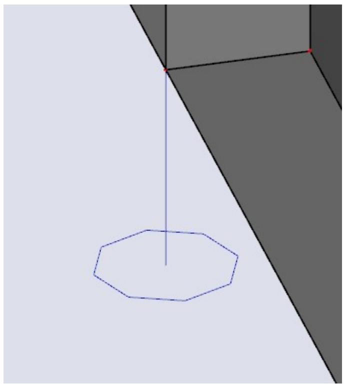
(b) 3D view that shows that the troughs continue in the cross beams.

Figure 7.2: Cut-out holes in SCIA Engineer.

Support conditions
One side of the bridge is hinged, as shown in Figure 7.3a. This means that it is rigid in the x, y, and z directions but free to rotate around Rx, Ry, and Rz. The other side of the bridge is sliding supported. Here, it is free in x, y, Rx, Ry, and Rz but rigid in z direction. These assumptions are supported in Section 9.3.



(a) Hinged support in SCIA Engineer.



(b) Sliding support in SCIA Engineer.

Figure 7.3: Different types of supports in SCIA Engineer.

Material properties
The OSD is made of steel grade S235. This applies to all the different sub-components (main girder, cross beams, and troughs). The other material properties are also constant throughout the deck and are shown in Table 7.2.

Property	Symbol	Value	Unit
Yield stress	σ_y	235	N/mm^2
Elasticity modulus	E	210000	MPa
Poisson ratio	ν	0.3	–
Density	ρ	7850	kg/m^3

Table 7.2: Material properties of the OSD.

An overview of the total OSD of the Freebrug can be seen in Figures 7.4 and 7.5.

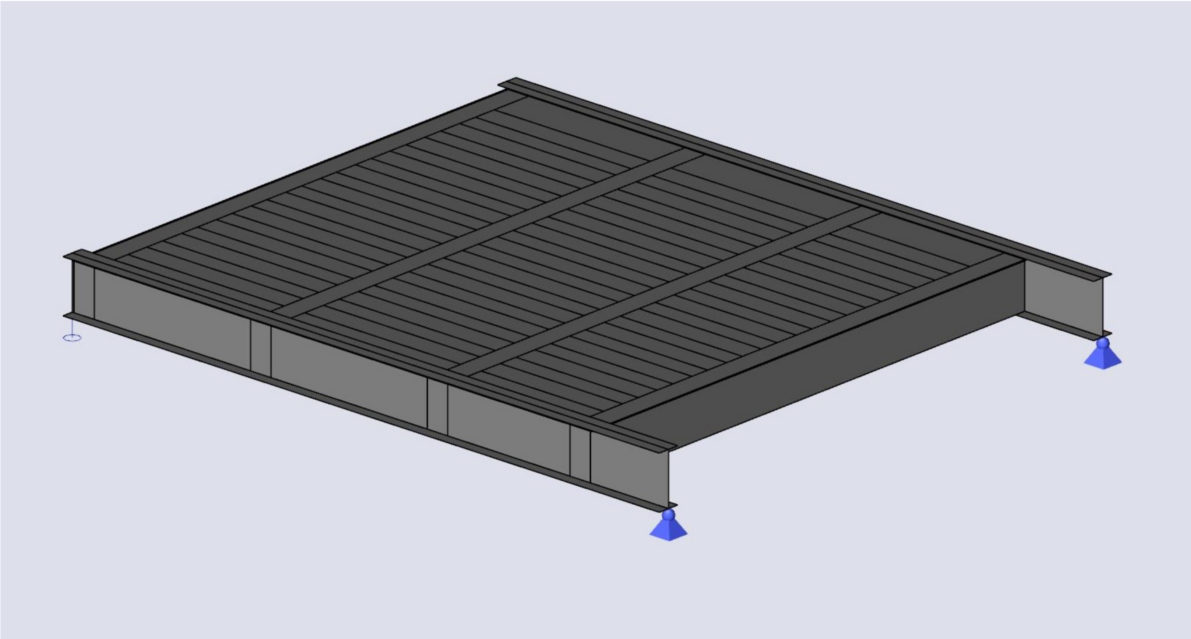


Figure 7.4: Overview of OSD in SCIA Engineer.

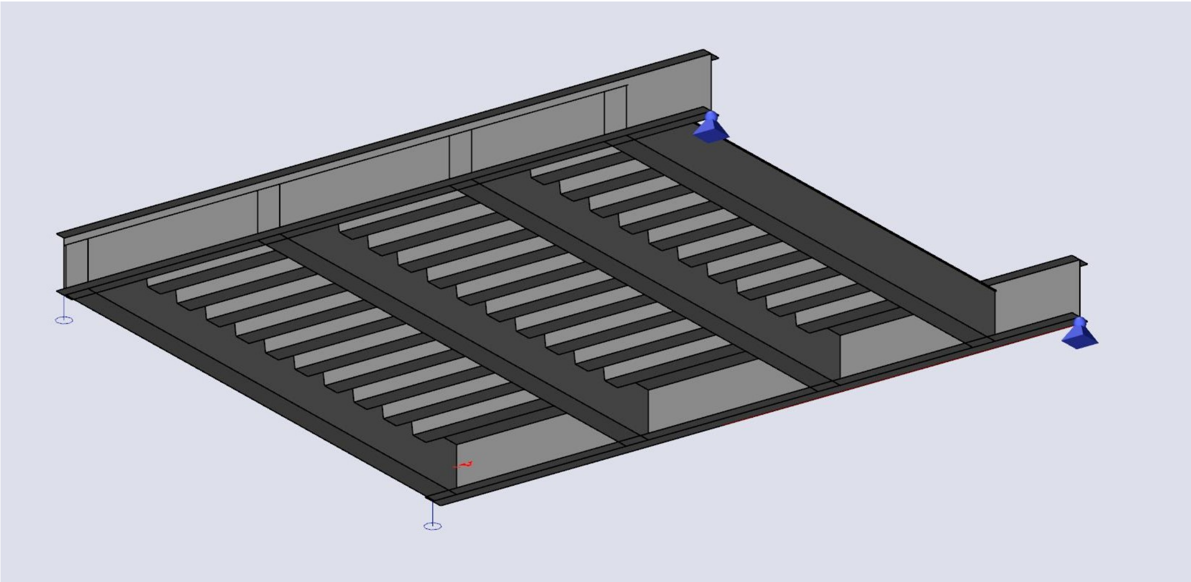


Figure 7.5: Bottom view of OSD in SCIA Engineer.

7.3. Loads and load combinations

The next step is to model the loads in SCIA Engineer. The governing loads are chosen that will be relevant for traffic bridges. Some loads that do occur are not included in the model, and the explanation for this can be found in Section 9.2. The loads that will be considered are:

- Self-weight, which is automatically calculated by SCIA Engineer. The software determines this based on the input dimensions of the plates, where the material type and its corresponding properties can also be specified. This is a permanent load.
- Cambering of the steel, which is included because the slight curvature of the deck is not modeled in SCIA Engineer. A value of $q = 0.50$ [kN/m²] is assumed for this based on NEN-EN 1993-2 (CEN-members, 2011). This is also a permanent load.
- Traffic load, which simulates the vehicles that can drive over the bridge. This is a variable load and is explained in more detail below.

7.3.1. Traffic load and lanes

The traffic loads can be found in NEN-EN 1991-2 (CEN-members, 2021b). Load Model 1 is applied, since this is the most suitable model for traffic consisting of lorries or cars. This model consists of double axle concentrated loads (Q_{ik}) and uniformly distributed loads (q_{ik}). The size of the axle loads is each 0.4 [m] x 0.4 [m].

- For lane number 1 holds: $Q_{ik} = 300$ [kN] and $q_{ik} = 9$ [kN/m^2]
- For lane number 2 holds: $Q_{ik} = 200$ [kN] and $q_{ik} = 2.5$ [kN/m^2]
- For lane number 3 holds: $Q_{ik} = 100$ [kN] and $q_{ik} = 2.5$ [kN/m^2]

See Figure 7.6.

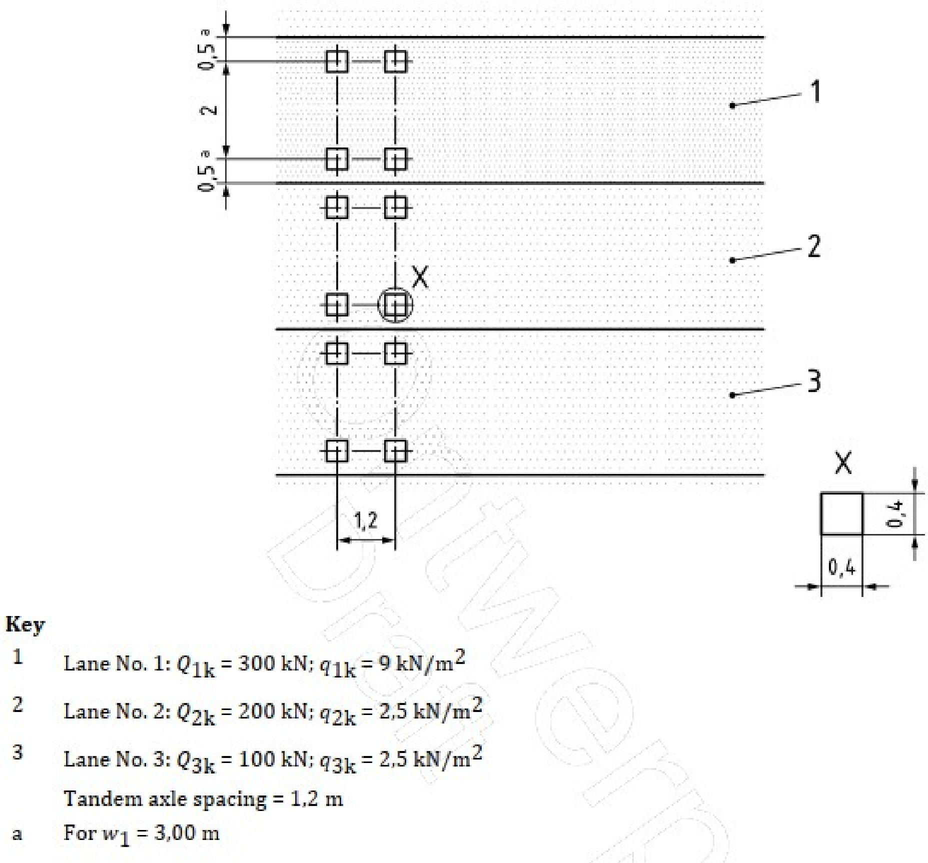


Figure 7.6: Load model 1 with 3 traffic lanes according to NEN-EN 1991-2 (CEN-members, 2021b).

Determining the traffic lanes for Freebrug

The Freebrug is a bridge with 2 traffic lanes. This can be concluded, because the width of the bridge is smaller than 3×3 [m] (each lane has $b = 3$ [m]), which means only 2 lanes fit. It should be determined where to position these traffic lanes on the deck. The first traffic lane should be positioned at the edge of the deck, since it is expected that high stresses will occur here. The second traffic lane will be placed directly next to it. The remaining section close to the other edge of the deck (since 2×3 [m] per lane $<$ total deck width) is not relevant for the analysis, as the bridge is symmetric. This remaining section is therefore excluded from the rest of the study.

Traffic lane 1 and traffic lane 2 can now be modeled in SCIA Engineer. Position 1 is an example of the axle loads of traffic load 1 ($Q_{ik} = 300$ [kN]) on traffic lane 1, as shown in Figure 7.7. These axle loads will be placed at every meter along the length of the deck. The translation of these axle loads by 1 meter to the left is shown as Position 2 in Figure 7.8. By shifting the axle loads one meter at a time, all possible traffic positions can be simulated. Furthermore, at the same time as the axle loads (Q_{ik}) for traffic lane 1, $q_{ik} = 9$ [kN/m^2] also applies on lane 1. Additionally to these loads, the values for traffic lane 2 for this situation are $Q_{ik} = 200$ [kN] and $q_{ik} = 2.5$ [kN/m^2].

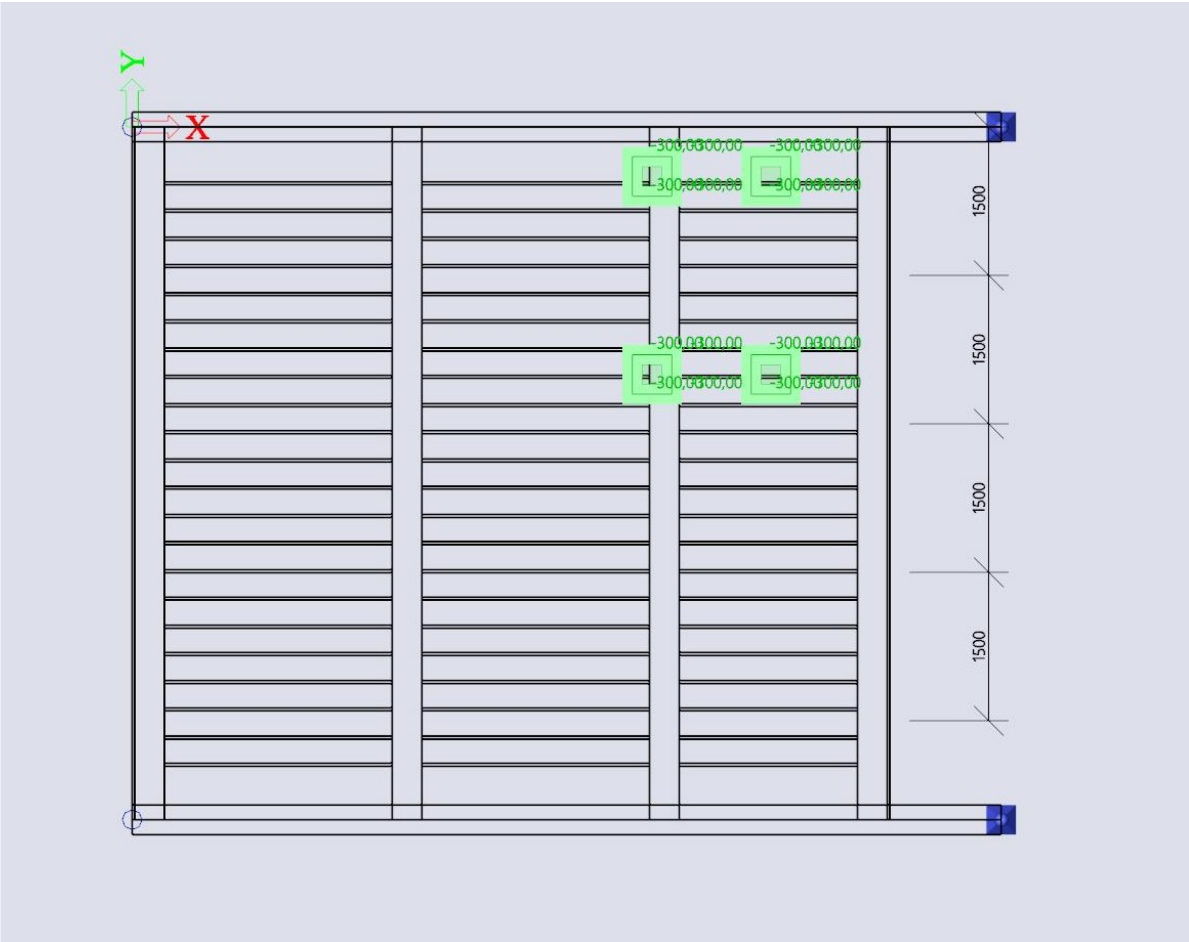


Figure 7.7: Traffic load on position 1 in SCIA Engineer.

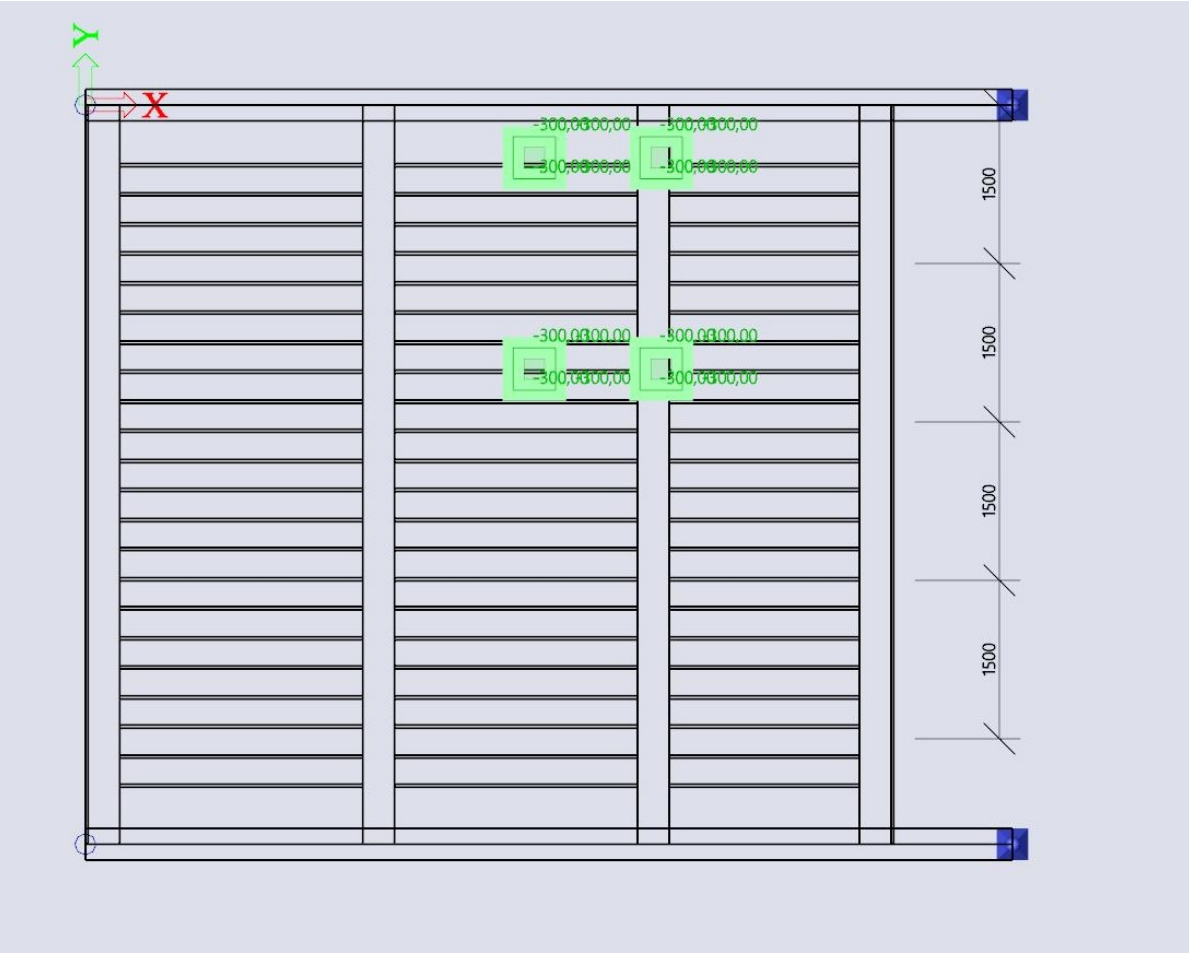


Figure 7.8: Traffic load on position 2 in SCIA Engineer (moving 1 [m] in the -x direction compared to position 1).

7.3.2. Load cases

Now that all loads have been explained, it must be clarified which loads can occur simultaneously and which are mutually exclusive.

- Self-weight will always be present (permanent load) and must always be included in the calculation for each component of the deck.
- The cambering load is also a permanent load and is only applied to the deck.
- Traffic loads are variable loads, meaning load cases need to be composed. If lane number 1 has $Q_{ik} = 300$ [kN] and $q_{ik} = 9$ [kN/m^2], then lane number 2 always has $Q_{ik} = 200$ [kN] and $q_{ik} = 2.5$ [kN/m^2]. The same applies vice versa: if lane number 2 has $Q_{ik} = 300$ [kN] and $q_{ik} = 9$ [kN/m^2], then lane number 1 always has $Q_{ik} = 200$ [kN] and $q_{ik} = 2.5$ [kN/m^2].

  For each possible position within a given traffic lane, only one position can be present per verification. This means that the relationship between all possible positions within a traffic lane is 'exclusive'.

7.3.3. Load combinations

Now, the load cases can be combined into load combinations. For the verification at the edge of the deck (traffic lane 1 is governing), the following loads will occur:

- Self-weight
- Steel cambering
- Traffic lane 1: $Q_{ik} = 300$ [kN] at all different positions (exclusive relation) and $q_{ik} = 9$ [kN/m^2]

- Traffic lane 2: $Q_{ik} = 200$ [kN] at all different positions (exclusive relation) and $q_{ik} = 2.5$ [kN/m^2]

For the verification in the 'middle' of the deck (traffic lane 2 is governing), the following loads will occur:

- Self-weight
- Steel cambering
- Traffic lane 1: $Q_{ik} = 200$ [kN] at all different positions (exclusive relation) and $q_{ik} = 2.5$ [kN/m^2].
- Traffic lane 2: $Q_{ik} = 300$ [kN] at all different positions (exclusive relation) and $q_{ik} = 9$ [kN/m^2]

7.3.4. Safety factors

To perform the checks for the SLS and ULS, safety factors must be applied. These are shown in Table 7.3. Fatigue assessment falls under the SLS check.

Type of load	Safety factor SLS	Safety factor ULS
Permanent	1.0	1.20
Variable	1.0	1.35

Table 7.3: Safety factors for different load types (CEN-members, 2011).

7.4. Critical locations for stress verifications

First, it will be investigated which locations in the deck experience high stresses due to the loads mentioned in Section 7.3. The stresses to be evaluated in SCIA Engineer are also referred to as '3D stresses', and this function can map the stresses for a specific selected 2D element. There is a choice of different types of 3D stresses to plot, such as in the x/y/z directions and whether the normal stress (σ) or shear stress (τ) is required. For finding the critical locations for stress verification, the normal stress in the x direction should be generated.

With cut-out holes

The 3D stresses are retrieved for all sub-components of the deck, for both ULS1 (traffic lane 1 maximum) and ULS2 (traffic lane 2 maximum), or respectively Figure 7.9 and Figure 7.10. From the model, it appears that the critical stress points for Figure 7.9 are located at the edge of the deck on the side of lane 1 at approximately the middle of the main girder span. This is logical, as the largest load is placed on this side of the deck, and the bending moment will also be the largest in the middle of the span. The same applies to Figure 7.10, but mirrored. The large load is now at the other edge and will therefore generate the largest stresses here as well, again in the middle of the main girder span where the bending moment is the greatest.

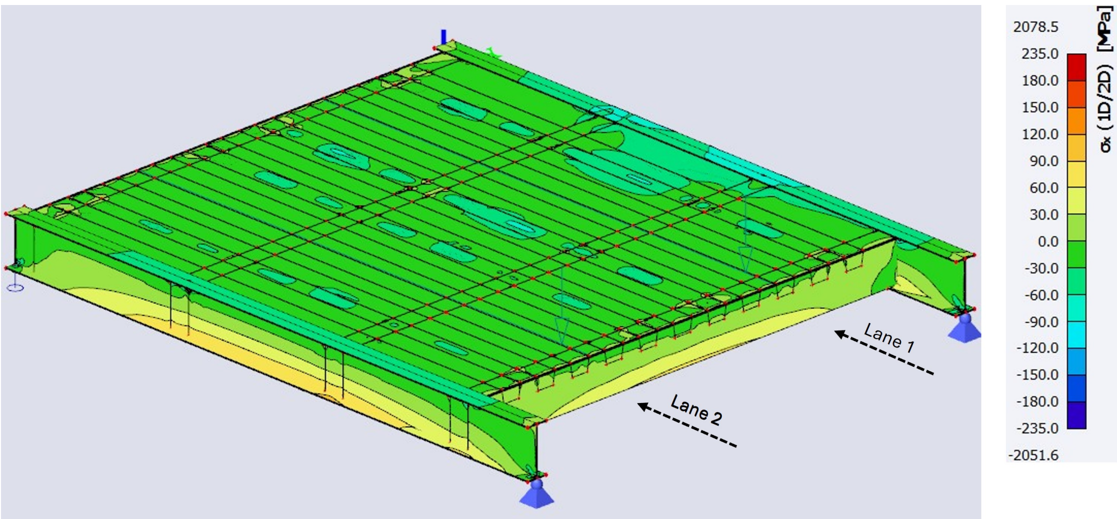


Figure 7.9: ULS traffic lane 1 maximum in SCIA Engineer.

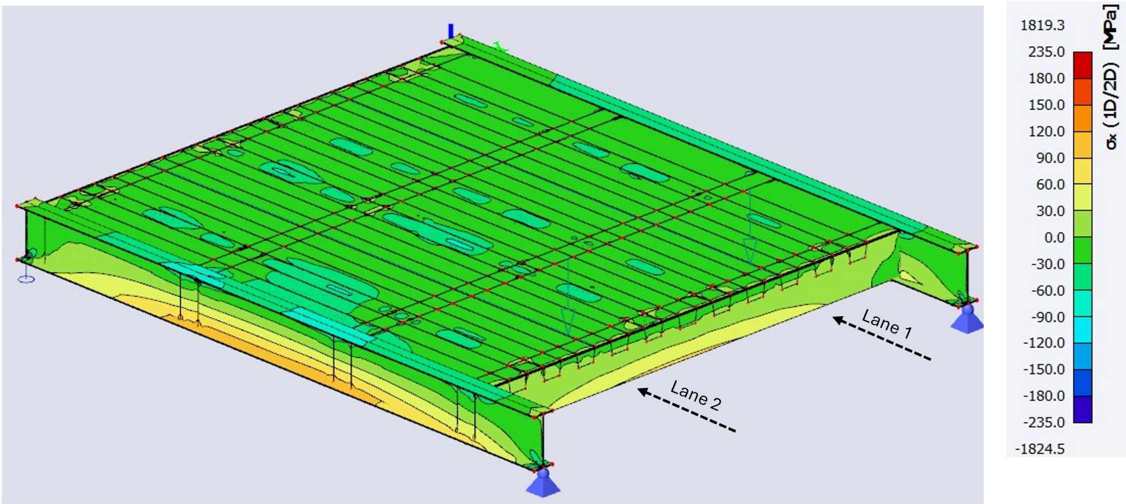


Figure 7.10: ULS traffic lane 2 maximum in SCIA Engineer.

The areas where stresses exceed | $\sigma_{(x)}$ | = 90 [MPa] (orange in the index column) are considered critical for stress due to ULS loads. This means that only a part of the sub-component will experience this stress, and it will not be uniform. The sub-components that are relevant for the corrosion check are*:

- main girder (1) top flange
- main girder (1) web
- main girder (1) bottom flange
- trough (1) bottom flange
- trough (2) bottom flange
- trough (5) bottom flange
- trough (5) left web
- trough (5) right web
- trough (6) bottom flange
- trough (7) bottom flange
- trough (7) left web
- trough (7) right web
- trough (10) bottom flange
- trough (11) bottom flange
- main girder (2) top flange
- main girder (2) web
- main girder (2) bottom flange

**The beam numbers are determined relative to the origin (0 point) of the axes. The closer a beam is to the origin, the lower the assigned number. In other words, main girder 1 passes through the origin of the axes, while main girder 2 is further away.*

These areas are critical for stress and will be included in the corrosion check. This is because if the cross section is further reduced due to corrosion, the material will have less resistance, resulting in higher stresses. This will be assessed in Section 8.1.

Without cut-out holes

For the model without cut-out holes, the same procedure is executed. This results in Figure E.1 and Figure E.2 from Appendix E. It turns out that all the sub-components mentioned above need to be checked, and additionally: trough (2) left web, trough (2) right web, trough (10) left web, and trough (10) right web.

Conclusions

The model has been built and the relevant loads have been applied. This revealed critical locations for stress that align with expectations, namely at the points where the loads were applied and at mid-span. The locations that need to be checked for corrosion damage in the next chapter have been identified for both types of models.

8 Determining damage

This chapter adds damage to the recently built model. First, corrosion damage is applied by reducing cross sections, and running the model for different future scenarios. Then, fatigue damage is introduced into the model, and various critical details are assessed. Finally, the combination of corrosion and fatigue is evaluated.

8.1. Corrosion damage

To determine the corrosion damage of the Freebrug, the documentation on the monitoring and maintenance of the bridge can be examined. However, proper documentation is missing, and only one visual inspection is carried out. Based on these photos, no corrosion is visible in the deck. However, these photos do not focus on details and are more intended to provide a general view of the bridge. Therefore, they are considered not useful for corrosion assessment, and the damage will need to be estimated in another way.

As described in Section 5.6.2, corrosion in the bridge deck is unlikely to occur uniformly. Since the documentation of the Freebrug does not provide useful information on actual corrosion locations, a reverse approach is adopted. Instead of starting from known damage, the focus is put on the locations identified as critical for stress in Section 7.4. If corrosion were to occur in these areas, it could pose a problem.

The phenomenon of corrosion leads to a reduction in cross section, which increases stresses according to Section 5.6.2. To account for this conservatively, a local reduction of dimensions will be applied in high-stress areas. The required reduction will be determined based on NEN standards for corrosion (CEN-members, 2012a,b).

8.1.1. Determining local reductions

According to Section 5.6.2, corrosion is strongly dependent on many factors in the environment, such as temperature, humidity, and the presence of corrosive substances. This is summarized in 6 so-called ‘corrosivity categories’, with which an estimate of the corrosion can be made (CEN-members, 2012b). The subdivision of these categories can be found in Appendix B.

These 6 classes are applied in NEN-EN-ISO standard 9224, which allows the estimation of corrosion attack values for metals and alloys exposed to natural outdoor atmospheres (CEN-members, 2012a). A distinction is made between two duration types of corrosion, namely in the initial period, which is the first 10 years, and steady-state corrosion for the years thereafter. This is done because the development of corrosion rates of metals exposed to natural outdoor atmospheres is not constant over the exposure time. For most metals, the corrosion rate decreases over time. This is because the corrosion products that form on the surface counteract further formation.

The progress of the corrosion can be represented in a linear manner when the total damage is plotted against time with a logarithmic scale. Or in formula form, the damage (D_C) is determined with Formula

8.1.

$$D_C = r_{\text{corr}} t^b \tag{8.1}$$

where

- D_C = total corrosion attack as mass loss per unit area [g/(m^2·a)]
- t = exposure time [y]
- r_{corr} = corrosion rate for the first year [g/(m^2·a)], see Appendix C (CEN-members, 2012b)
- b = metal-environment-specific time exponent (usually < 1)

And this time exponent 'b' can be filled in in two ways, namely with B1 and B2 (CEN-members, 2012a).

- B1 values represent the average time component
- B2 values represent the upper limit of corrosion attack (two standard deviation additions are done)

Values for B1 and B2 can be found in Appendix D. By filling in the 'b' value and time the total damage attack can be determined up to 100 years of corrosion.

Beyond 20 years of exposure, the formula changes and the corrosion damage can be calculated according to Formula 8.2.

$$D_C(t > 20) = r_{\text{corr}} \left[20^b + b \left(20^{(b-1)} \right) (t - 20) \right] \tag{8.2}$$

The mass loss per unit area (D_C) is given in g/m^2. This can be converted into a thickness reduction (Δt) according to Formula 10.1.

$$\Delta t = \frac{D_C}{\rho} \tag{8.3}$$

where

- Δt = thickness reduction [mm]
- D_C = corrosion attack in [g/m^2]
- ρ = density of steel (≈ 7850 [kg/m^3] $= 7.85$ [g/cm^3]).

Then the cross sections can be reduced with the calculated thickness reduction.

8.1.2. Filling in the values

First, a corrosivity class must be chosen that matches the climate around the Freebrug, according to Appendix B. It is an outdoor climate, and the bridge is located in a rural area/small town. This corresponds to class C2, with low corrosivity. Additionally, the formula will also be applied for class C3, as it has been found that no maintenance has been performed on the bridge, causing it to age more quickly.

The bridge has been in place for 45 years, so Formula 8.2 will be applied. For B, values will be calculated for both B1 (average) and B2 (upper limit) to compare the difference. All values for the variables are listed in Table 8.1.

Corrosivity category	r_{corr} **[g/m^{2}a]**	**b val. (B1) [-]**	**b val. (B2) [-]**	**Time [y]**	**t val. (B1) [-]**	**t val. (B2) [-]**
C2	$10 < r_{\text{corr}} \leq 200$	0.523	0.575	45	7.322	8.925
C3	$200 < r_{\text{corr}} \leq 400$	0.523	0.575	45	7.322	8.925

Table 8.1: Corrosion rate and corresponding values (CEN-members, 2012b).

One example for filling in Formula 8.2 with the top row values for B1 is given in Formula 8.4.

$$D_{C2}(t=45,B1)=\frac{10+200}{2}\left[20^{0.523}+0.523\left(20^{(0.523-1)}\right)(7.322-20)\right]=336.287[g/(m^2a)] \quad (8.4)$$

All the other values will be done the same way so that in the end Table 8.2 is computed. It can be seen that the higher the corrosivity class, the higher the thickness reduction. This is as expected because a higher corrosion environment has been applied. Additionally, the values where B2 is chosen should be higher than the values where B1 is used, as B2 represents the upper limit. This also aligns with the obtained thickness reductions.

Corrosion attack	D_C [g/m^2a]	Δt [mm]
$D_{C2}(t=45,B1)$	336.3	0.04
$D_{C2}(t=45,B2)$	400.9	0.05
$D_{C3}(t=45,B1)$	960.8	0.12
$D_{C3}(t=45,B2)$	1144.8	0.15

Table 8.2: Calculation of thickness reduction (CEN-members, 2012b).

Prediction of damage for reuse purposes

When the deck is reused, it will have extended service life. To simulate future conditions, several scenarios are chosen. In these scenarios various outside conditions are selected, ranging from low corrosive environments to high environments, in order to find out what the effect is on the thickness reduction of the profiles.

- Scenario 1: additional service life of 25 years - C2
- Scenario 2: additional service life of 50 years - C2
- Scenario 3: additional service life of 25 years - C3
- Scenario 4: additional service life of 50 years - C3
- Scenario 5: additional service life of 25 years - C4
- Scenario 6: additional service life of 50 years - C4
- Scenario 7: additional service life of 25 years - C5
- Scenario 8: additional service life of 50 years - C5

For example, in Scenario 1, the total service life is given by $t_{tot}=45+25=70$ years, with exposure class C2. The governing current corrosion attack (D_{C3}) from Table 8.2 is added to the expected future corrosion attack ($D_{C,tot}$). Using these values, the expected thickness reductions for each scenario can be determined, as shown in Table 8.3. To remain on the conservative side, the parameter 'b' is chosen as B2.

Scenario	Corrosivity category	r_{corr} [g/m^{2}a]	b val. (B2) [-]	Time [y]	t val. (B2) [-]	$D_{C,fut}$ [g/m^{2}a]	$D_{C,tot}$ [g/m^{2}a]	Δt [mm]
1	C2	$10 < r_{\text{corr}} \leq 200$	0.575	25	6.365	356.4	1732.3	0.22
2	C2	$10 < r_{\text{corr}} \leq 200$	0.575	50	9.482	410.1	1786	0.23
3	C3	$200 < r_{\text{corr}} \leq 400$	0.575	25	6.365	1021.2	2397.1	0.31
4	C3	$200 < r_{\text{corr}} \leq 400$	0.575	50	9.482	1171.7	2547.6	0.32
5	C4	$400 < r_{\text{corr}} \leq 650$	0.575	25	6.365	1787.1	3163	0.40
6	C4	$400 < r_{\text{corr}} \leq 650$	0.575	50	9.482	2050.51	3426.4	0.44
7	C5	$650 < r_{\text{corr}} \leq 1500$	0.575	25	6.365	3659.32	5035.2	0.64
8	C5	$650 < r_{\text{corr}} \leq 1500$	0.575	50	9.482	4198.7	5574.6	0.71

Table 8.3: Prediction of corrosion damage for additional service life of 25 years and 50 years (CEN-members, 2012b).

8.1.3. Critical locations for corrosion verification

As described in Section 7.4, certain areas of the deck turned out critical for stress verifications and these need to be examined for corrosion effects. Based on Table 8.3, it has been decided to further develop scenarios 1 ($\Delta t = 0.22$ [mm]), scenario 5 ($\Delta t = 0.40$ [mm]), and scenario 8 ($\Delta t = 0.71$ [mm]). This will allow for the examination of the effects of the lower limit, upper limit, and the middle value. This reduction will be applied to the areas identified in Section 7.4. An example of such a cross section reduction is shown in Figure 8.1.

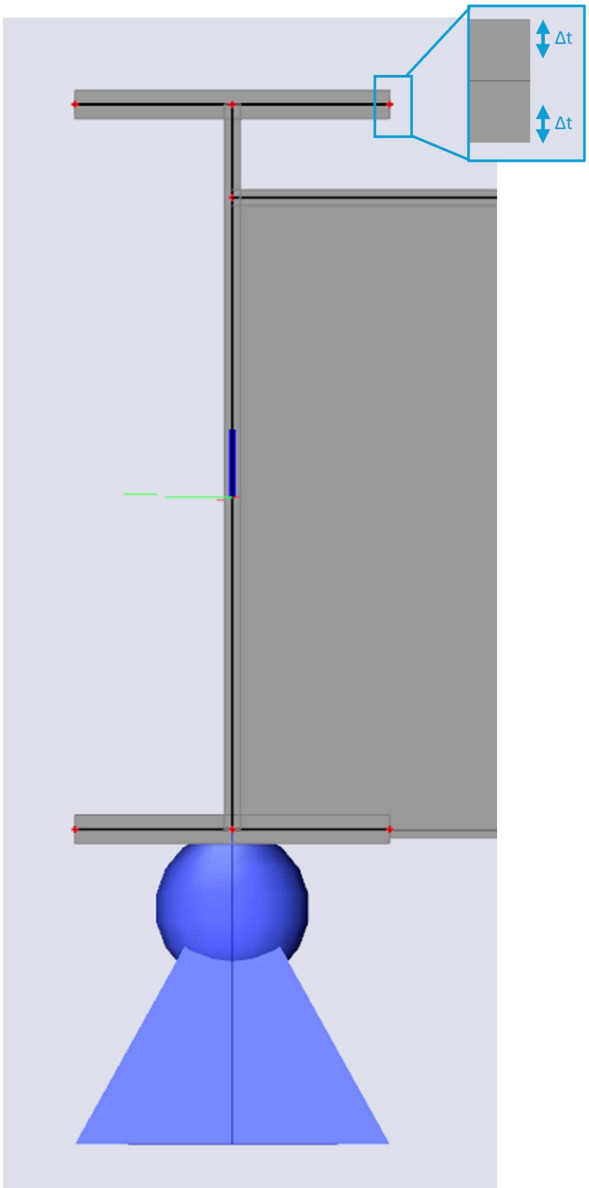


Figure 8.1: Schematization of thickness reduction (not on scale) in SCIA Engineer.

Conclusions scenario 8 (with cut-out hole)

For scenario 8, a thickness reduction of $\Delta t = 0.71$ [mm] is applied. This results in the following stress outcome for ULS2 (heavy load on lane 2), as shown in Figure 8.2. Overall, the stress in the entire OSD increases slightly compared to Figure 7.10. This is expected, as the material has lower resistance due to reduced dimensions. This higher stress is particularly noticeable in the top flange of the main girder (2), as indicated by the colors. The bottom view of this is shown in Figure 8.3, where it can be seen that the bottom flange of trough 7 reaches high stresses. In the middle, a stress range of between 150 [MPa] and 180 [MPa] occurs. This is the location with the highest UC of the deck. For ULS1 (heavy load on lane 1), the same pattern can be observed, but this time in the middle of trough 5. In short, trough 7 and trough 5 are the most critical areas of the deck in terms of corrosion, but do not fail. The other areas of the deck are not critical and will easily withstand under scenario 8.

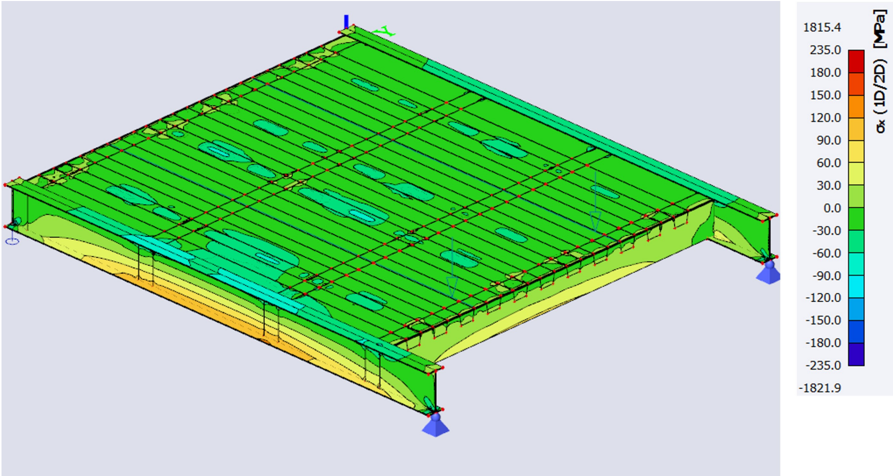


Figure 8.2: 3D stress verification with reduced cross sections in SCIA Engineer.

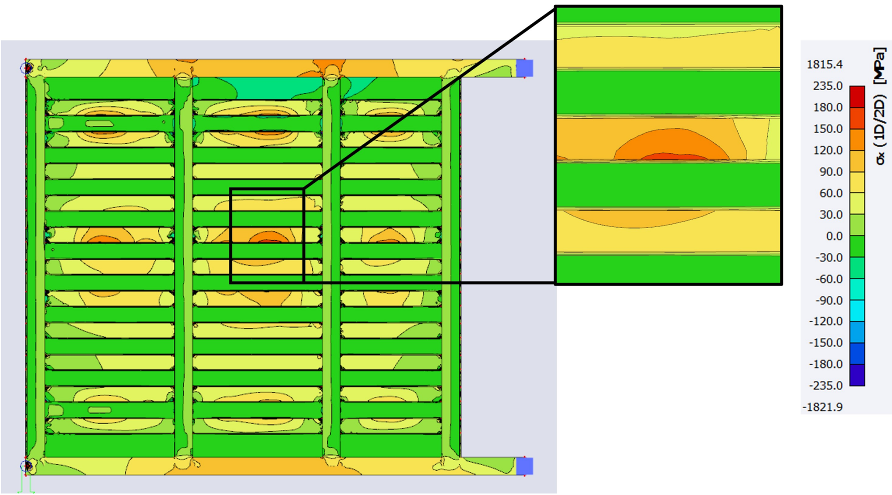


Figure 8.3: 3D stress verification bottom view with zoomed-in detail of trough 7 in SCIA Engineer.

Conclusions scenario 8 (without cut-out hole)
Again for scenario 8, a thickness reduction of $\Delta t = 0.71$ [mm] is applied, but now for the model without cut-out holes. The results of the stresses in the deck are shown in Appendix E in Figure E.3 and the bottom view is depicted in Figure E.4. The effect of corrosion for this model is similar to the effect for the model with cut-out holes. So again, the stress in the entire OSD increases slightly compared to Figure E.1, due to lower resistance and the most critical troughs are trough 5 (ULS1) and trough 7 (ULS2). The stresses in these throughs only reach a $\sigma_{max} \approx 150$ [MPa], which is a bit lower compared to the previous model. So the troughs will withstand the stresses.

Furthermore, one difference compared to the previous model is that higher stresses occur on the lower flanges of the main girders, as seen in the left zoom-in of Figure E.4. These higher stresses are not significant and will also only reach a $\sigma_{max} \approx 150$ [MPa]. In short, it can be concluded that, trough 7, trough 5 and the bottom flanges of both main girders are the most critical areas of the deck, in terms of corrosion, but do not fail. Other areas of the deck will easily bear the forces under scenario 8. Besides to that, it is noted that there is a difference in stress distribution between the two models, with the model containing cut-out holes transferring more load through the troughs, while the model without cut-out holes transfers more load to the main girders.

→ **Since scenario 8 will not fail for both types of models, which already has the largest thickness reduction, it is not necessary to check scenario 1 and scenario 5 since they automatically will not fail.**

8.2. Fatigue damage

Fatigue damage will also occur in the deck, in addition to corrosion. As explained, proper documentation on monitoring and maintenance of the Freebrug is missing, and only a visual inspection has been carried out. Although damage from fatigue is mostly not visible to the naked eye, it can still be present and therefore needs to be considered in the modeling.

According to NEN EN 1993-2 for steel bridges, a fatigue assessment is not required for (CEN-members, 2011):

- Pedestrian bridges, canal bridges, or other bridges that are primarily subjected to static loads.
- Certain components of road or railway bridges that are not exposed to traffic loading.

Thus, fatigue assessment is only required for bridges subjected to heavy loads that have undergone many cycles. The number of cycles can be determined from the traffic loading history of the bridge.

8.2.1. Fatigue Load Model 3

For road bridges, the loading can be modeled using a Fatigue Load Model (FLM). NEN-EN 1991-2 describes five different FLMs, each with a different approach to determining fatigue. FLM3 has been chosen and will be further explained in this thesis, because it can be used for the direct verification of designs through a simplified method. This model uses a single type of vehicle with a corresponding yearly intensity. For certain types of bridges, such as larger steel bridges, like the Van Brienenoord Bridge, FLM4 should be used (Guijt, 2023). The Freebrug is a relatively small regional bridge, and therefore FLM3 will be explained in more detail.

FLM3 is represented by four axle loads, each with two identical wheels. A schematic representation of FLM3 can be seen in Figure 8.4. This model uses a single vehicle instead of a range of different vehicles and multiple configurations. The vehicle is represented by an axle load of 120 [kN].

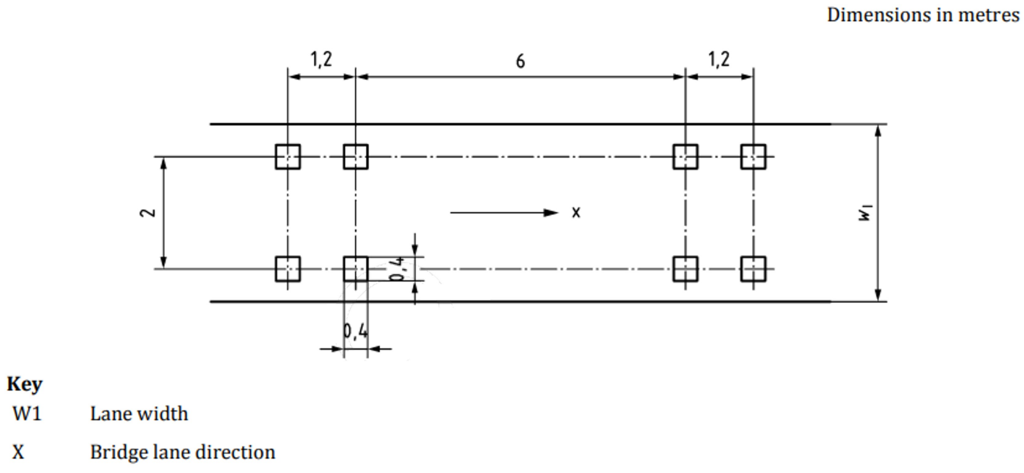


Figure 8.4: Fatigue load model 3 (CEN-members, 2021b).

The application of FLM3 in the FE model at example position 1 can be seen in Figure 8.5, and at example position 2 in Figure 8.6. The axle loads are moved 1 meter at a time along the length of the bridge to simulate all possible traffic positions, similar to what was done for the traffic load (Load Model 1) in Section 7.3.1*.

**According to NEN-EN 1991-2, there are also multiple wheel positions (5 in total) across the width of the deck, with the central position accounting for 50% of the cases (CEN-members, 2021a). Therefore, only this central position is used in the analysis.*

Figure 8.5: FLM3 shown on position 1 in SCIA Engineer.

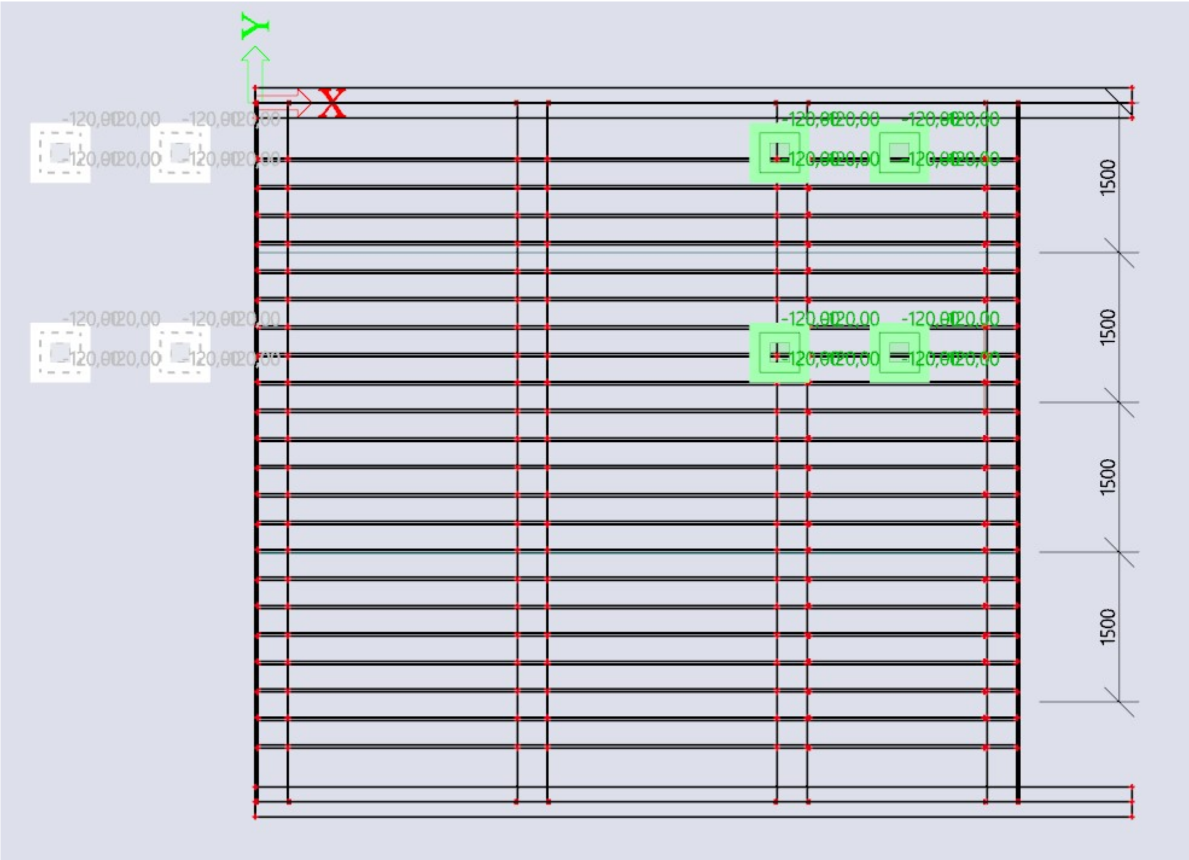


Figure 8.6: FLM3 shown on position (moving 1 [m] in the -x direction compared to position 1) in SCIA Engineer.

8.2.2. Loading history

The next step to determine the fatigue damage, is estimating or measuring the loading history. For the Freebrug, an assumption has already been made by Sweco, as shown in Table 8.4. The deck is freely accessible to all traffic.

Intensities [per day]	Motor vehicles	Agricultural traffic	(Moped) cyclists	Pedestrians	Total
Freebrug	509	1	60	6	576

Table 8.4: Traffic intensities on Freebrug per day obtained from dossier of Sweco.

The bridge was built in 1980, which means it has existed for 45 years. According to the dossier of Sweco, the estimated number of heavy vehicles that have crossed the bridge is:

$$N \approx (509 + 1) \times 365 \times 45 \approx 8,376,750 \text{ [heavy vehicles]} \tag{8.5}$$

However, this is an overestimation. Traffic intensities have increased in recent years, and the number of vehicles in the early years of the bridge's existence was likely lower. However, to remain on the conservative side, this number is assumed for all 45 years.

8.2.3. Governing details - critical locations for fatigue verifications

Not all parts of the deck will experience the same amount of fatigue damage. As explained in the literature review on fatigue, Section 5.6.1, welds will contain local peak stresses and be susceptible for fatigue cracks.

It is necessary to evaluate which details of the deck should be assessed. Research shows that the weld between the trough and the deck plate accounts for more than 80% of all fatigue cracks (Zeng et al., 2023). Another important and vulnerable detail is the joint between the trough and cross beam (Fang et al., 2021). These two details described occur multiple times in the deck, because the deck is made up of several cross beams and troughs, meaning there are multiple instances of these connections. Therefore, the first step is to analyze where the critical detail for each 'type' is located. This is done by applying the SLS fatigue load to the deck and analyzing its effect. This will be further analyzed for fatigue damage, both for continuous and discontinuous troughs.

With cut-out hole

In Figure 8.7, the details that could be critical for the deck to trough connection are shown. Additionally, in Figure 8.8, the critical detail for the joint between the cross beam and the continuous trough can be seen. The determination of when a detail is critical is based on the color and therefore the stress level. Stress values will later need to be determined for these specific critical areas.

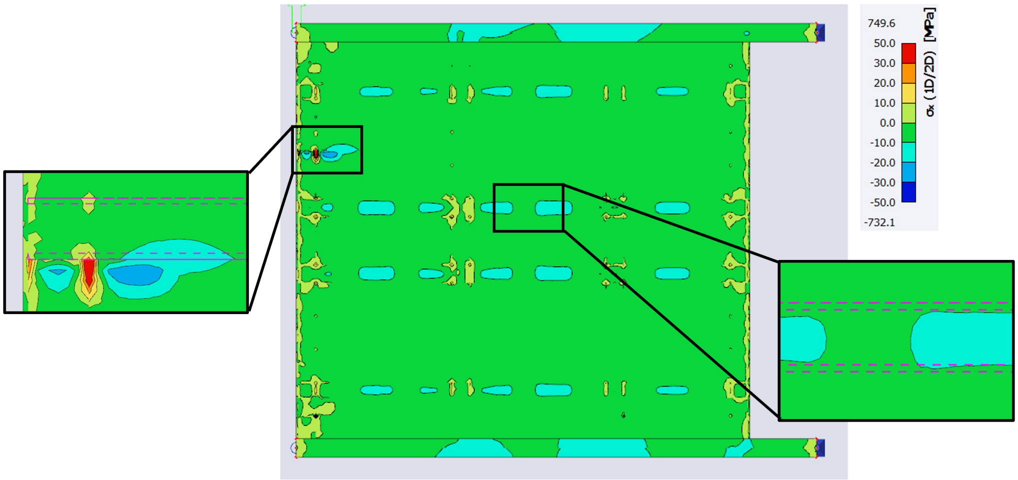


Figure 8.7: Stresses due to SLS fatigue loading, zooming in on possible governing details for trough to deck weld in SCIA Engineer.

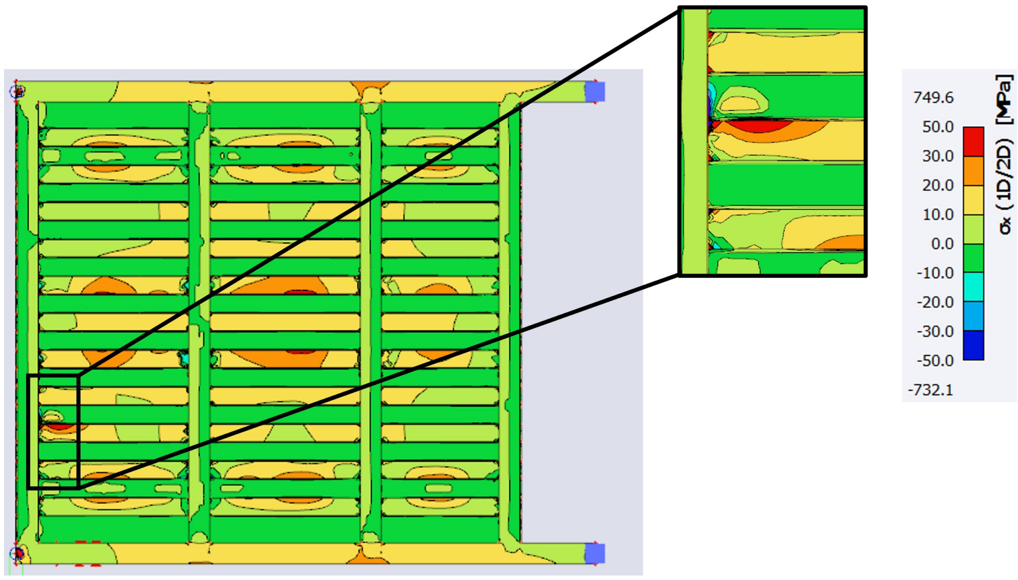


Figure 8.8: Stresses due to SLS fatigue loading, zooming in on governing detail for continuous trough to cross beam joint in SCIA Engineer.

Without cut-out hole

The same procedure has also been applied to the model with discontinuous troughs. In Figure E.5 in Appendix E, the critical details for the deck to trough connection can be seen. Furthermore, in Figure E.6 in Appendix E, the critical detail for the joint between the cross beam and the discontinuous trough is shown. Again, whether a detail is critical has been determined by the color, indicating the stress level, and later the specific value of these stresses will be determined.

8.2.4. Detail categories

According to NEN-EN 1993-1-9-2024 (CEN-members, 2024), the appropriate detail categories can be selected for an orthotropic deck with (dis)continuous stiffeners associated with the chosen details. The detail category provides the reference fatigue strength ($\Delta\sigma_C$), allowing the corresponding fatigue curve to be chosen for the fatigue assessment. These different curves are shown in Figure 5.8 in Section 5.6.1.

Detail 1.1: Weld between trough and deck (with cut-out hole)

The most common fatigue-related damage occurs in the detail between the deck plate and a trough. This detail is shown in Figure 8.9. The stress direction, as indicated by the arrow, is determined by the normal tensile stress in the deck plate, or in other words 'σ_{x+}' in SCIA Engineer.

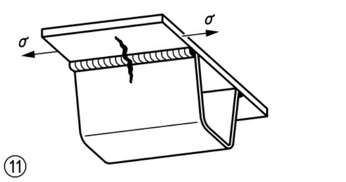
Detail category [a]	Constructional detail	Symbol	Description	Supplementary Requirements
112		As ①/112 in Table 10.3	⑪ Deck plate to stiffener web joint, subject to normal stress	Δσ should be calculated using normal stress in the deck plate at the location of the joint. See ①, ③ or ⑥ of Table 10.3.
100		As ③ in Table 10.3		
		As ⑥ in Table 10.3		

Figure 8.9: Detail category for trough to deck weld according to NEN-EN 1993-1-9-2024 (CEN-members, 2024).

Detail 1.2: Trough to cross beam joint (with cut-out hole)

The second detail that is examined is shown in Figure 8.10. The stress should be calculated using normal tensile stress in the bottom flange of the trough, or in other words 'σ_{x+}' in SCIA Engineer again.

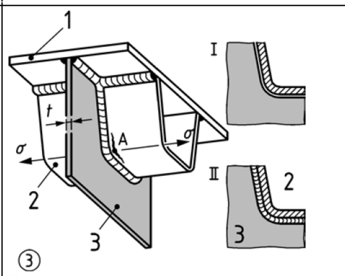
Detail category [a]	Constructional detail	Symbol	Description	Supplementary Requirements
71	 ③ **Key** 1 deck plate 2 continuous stiffener 3 cross beam I before welding II after welding		③ As ①, but with close fit cut-out in crossbeam ① Continuous stiffener to cross-beam joint with extended cut-out in crossbeam subject to normal stress in stiffener, stiffener failure, crossbeam web thickness t > 12mm	Δσ should be calculated using normal stress in the stiffener bottom flange (spot 'A').

Figure 8.10: Detail category for continuous trough to cross beam joint according to NEN-EN 1993-1-9-2024 (CEN-members, 2024).

Detail 2.1: Weld between trough and deck (without cut-out hole)

The detail that needs to be analyzed is the same as in Figure 8.9, which is the potential crack between the deck plate and the trough. Also for this type of model, the normal tensile stress in the deck plate must also be determined, or in other words, 'σ_{x+}' in SCIA Engineer.

Detail 2.2: Trough to cross beam joint (without cut-out hole)

The detail that must be considered is shown in Figure 8.11, which is the joint of discontinuous troughs to the cross beam. For this, it is again necessary to calculate the normal stress in the bottom flange of the trough (σ_{x+}).

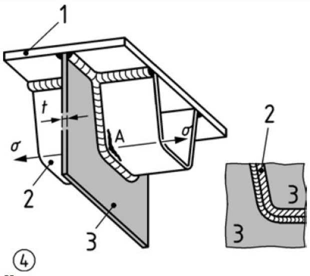
Detail category [a]	Constructional detail	Symbol	Description	Supplementary Requirements
71	 **Key** 1 deck plate 2 discontinuous stiffener 3 cross beam	ν	④ Discontinuous stiffener to crossbeam joint (crossbeam separates stiffeners) subject to normal stress in stiffener, with full penetration butt welds, stiffener failure	Δσ should be calculated using normal stress in the stiffener bottom flange

Figure 8.11: Detail category for discontinuous trough to cross beam joint according to NEN-EN 1993-1-9-2024 (CEN-members, 2024).

8.2.5. Reading the stress values from FEM

In Figure 8.12, the stress values were read for detail 1.2 at a distance of 10 [mm] from the intersection node. This was also done at a location 15 [mm] from the intersection in Figure 8.13. The stress difference should be calculated according to Formula 8.6.

$$\Delta\sigma = |\sigma_{\text{FLM,max}} - \sigma_{\text{FLM,min}}| \tag{8.6}$$

This can be done for all details, and the average '$\Delta\sigma$', from both distances, is summarized in Table 8.5.

With cut-out hole

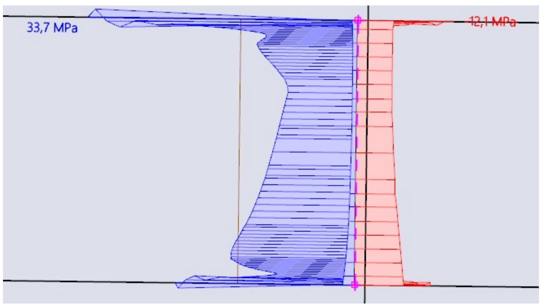


Figure 8.12: Stress values for section at 10 [mm] from intersection node.

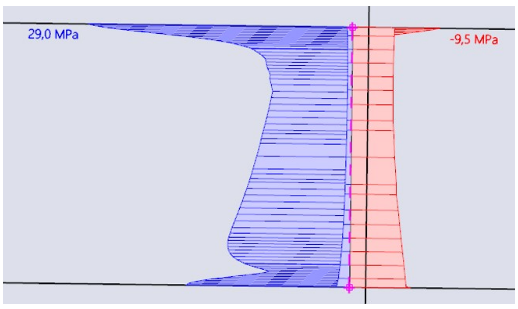


Figure 8.13: Stress values for section at 15 [mm] from intersection node.

Without cut-out hole
The same procedure is performed and the results can be found in Table 8.5.

	Detail number	$\Delta\sigma$ [MPa] at d = 10 [mm]	$\Delta\sigma$ [MPa] at d = 15 [mm]	$\Delta\sigma$ average [MPa]
With cut-out hole	1.1 (plate trough)	55.0	45.4	50.2
	1.2 (cross beam trough)	45.8	38.5	42.2
Without cut-out hole	2.1 (plate trough)	18.1	15.3	16.7
	2.2 (cross beam trough)	38.5	29.2	33.9

Table 8.5: Overview of stress values obtained from FEM for fatigue damage.

8.2.6. Fatigue check

Now the damage can be calculated for the chosen details. The S-N curve can be used to determine which N corresponds to the calculated $\Delta\sigma$. This is then compared to the number of cycles that have already occurred on the bridge per slow lane. The damage number for fatigue (D_F) is then determined using Formula 8.7, also known as the Palmgren-Miner rule. All results are summarized in Table 8.7.

$$D_F = \Sigma \frac{N_{\text{pas}}}{N_{\text{SN curve}}} \tag{8.7}$$

Detail number	Detail category [MPa]	N_{pas}	$N_{SNcurve}$	Damage number [-]	OK?
1.1	112	4.2×10^6	6.9×10^7	0.06	✓
1.2	71	4.2×10^6	1.8×10^7	0.23	✓
2.1	112	4.2×10^6	∞	0.00	✓
2.2	71	4.2×10^6	4.1×10^7	0.10	✓

Table 8.6: Damage numbers obtained from FEM for all considered details.

Conclusions
Based on Table 8.7, it can be observed that the damage numbers for details 1.1 and 2.1 (plate to trough) are very low, namely 0.06 and 0.00. For details 1.2 and 2.2 (trough to cross beam), the damage numbers are slightly higher, namely 0.23 and 0.10. So both types of models show the same pattern and are therefore in alignment. In short, all values are currently within acceptable limits, as D < 1. This means that the welds between both the trough and deck, as well as the trough and cross beam, currently meet requirements.

Both types of models, with and without cut-out holes, show the same order of magnitude in terms of damage numbers. The damage values in the model without cut-out holes are lower for both details compared to the model with cut-out holes. This may be due to the fact that the model with cut-out holes has less resistance at the locations where the trough passes through the cross beam, as a hole is present there, which leads to higher stresses. Based on this data, regarding fatigue damage having an OSD without cut-out holes is therefore more preferable.

8.2.7. Prediction of future for reuse purposes

However, the previous conclusions only reflect the current state. To assess the potential for reuse, a projection into the future is needed. The chosen future scenario assumes an additional lifetime of 50 years. If the traffic intensity remains the same as in the past, an estimate can be made of the expected axle loads over these 50 years in the future, referred to as N_{fut}.

The $N_{\text{SN curve}}$ value will not change by assuming a specific future scenario, as this represents the maximum capacity according to the curve. Once again, the damage value can be calculated using Equation 8.7.

Detail number	Detail category [MPa]	N_{fut}	$N_{SNcurve}$	Damage number [-]	OK?
1.1	112	8.8×10^6	6.9×10^7	0.13	✓
1.2	71	8.8×10^6	1.8×10^7	0.49	✓
2.1	112	8.8×10^6	∞	0.00	✓
2.2	71	8.8×10^6	4.1×10^7	0.21	✓

Table 8.7: Damage numbers obtained from FEM for all considered details.

Conclusions
Even with a future service life of 50 [y], the damage values will remain below 1, meaning failure will not occur in this situation. If the damage value turns out to be too high, it is possible to implement certain measures. An example of such measures, based on detail 1.1, is given below:

If D_F does not satisfy, measures for decreasing the damage number detail 1.1:

- The endurance limit for a detail category of 112 [N/mm^2] is 47 [N/mm^2], while the current stress range is 50.2 [N/mm^2]. Therefore, axle load limitation could be a viable option to possibly give this detail 'endless' lifetime. A new run of the model without heavy loads is required to determine the exact effect of load restrictions.
- The additional service life may be reduced if the number of additional load cycles becomes too high. In the example described, the total allowable number of cycles is 6.9×10^7, while the projected number of future cycles is 8.8×10^6, which is lower and therefore acceptable. If it turns out that more cycles are required than are available, the additional lifetime should be reduced accordingly.

If D_F does not satisfy, measures for decreasing the damage number detail 1.2:

- The endurance limit for a detail category of 71 [N/mm^2] is 30 [N/mm^2], while the current stress range is 42.2 [N/mm^2]. Therefore, axle load limitation could be a viable solution to possibly give this detail 'endless' lifetime. A new run of the model without heavy loads is required to determine the exact effect of load restrictions.
- The additional service life may be reduced if the number of additional load cycles becomes too high. In the example described, the total allowable number of cycles is 1.8×10^7 [cycles], while the projected number of future cycles is 8.8×10^6, which is lower and therefore acceptable. If it turns out that more cycles are required than are available, the additional lifetime should be reduced accordingly.

Detailed fatigue assessment
It should be mentioned that the described method for fatigue assessment is a simplified procedure. For traffic bridges with large heavy loads and high intensities such as the Van Brienenoord bridge, FLM4 is advised and all details of the deck plate, troughs, cross beams, and all connections must be separately examined (CEN-members, 2011, 2012c; Guijt, 2023).

In these details where the stress range comes together from the combined effects of the bending of the bridge and the bending of internal parts, this must also be taken into account. A combined assessment is needed of local effects and global effects.

Furthermore, for larger types of traffic and railway bridges, it is recommended to do additional tests so that cracks are clearly mapped. These tests are called 'Non-Destructive Tests' (NDTs) and mean, for example, an ultrasonic scan or infrared scan (Shanmugham and Liaw, 1996). With this scan, exact information about the condition of the bridge can be determined to act safely to prevent problematic consequences.

8.3. Corrosion Fatigue damage

The combination of corrosion and fatigue should, as discussed in Section 5.7, also be taken into consideration. To account for this phenomenon, the previously described procedures for corrosion and fatigue will be combined. So this means that both a thickness reduction of the cross section will be added, and the chosen fatigue details will be examined.

For the thickness reduction, the thickness reduction corresponding to Scenario 8 will be applied, meaning an additional service life of 50 years. So to read the damage number from the S-N curve, the number of cycles over 95 [y] should be taken into consideration. This would mean $N_{pas} = 8.8 * 10^6$ [cycles] again.

So to have a consistent approach and be able to compare the results, for Corrosion Fatigue immediately a prediction in the future of an additional 50 [y] is made.

8.3.1. Prediction of future for reuse purposes

Once again, the Corrosion Fatigue damage number (D_{CF}) can be calculated with Formula 8.8.

$$D_{CF} = \Sigma \frac{N_{\text{pas}}}{N_{\text{SN curve}}} \tag{8.8}$$

The values are presented in Table 8.8 and Table 8.9.

	Detail number	$\Delta\sigma$ [MPa] at d = 10 [mm]	$\Delta\sigma$ [MPa] at d = 15 [mm]	$\Delta\sigma$ average [MPa]
With cut-out hole	1.1 (plate trough)	55.2	45.7	50.5
	1.2 (cross beam trough)	47.9	40.2	44.1
Without cut-out hole	2.1 (plate trough)	18.2	16.1	17.2
	2.2 (cross beam trough)	51.9	42.2	47.1

Table 8.8: Overview of stress values obtained from FEM for both corrosion and fatigue damage.

Detail number	Detail category [MPa]	N_{fut}	$N_{SNcurve}$	Damage number [-]	OK?
1.1	112	8.8×10^6	7.0×10^7	0.13	✓
1.2	71	8.8×10^6	1.3×10^7	0.68	✓
2.1	112	8.8×10^6	∞	0.00	✓
2.2	71	8.8×10^6	1.0×10^7	0.88	✓

Table 8.9: Damage numbers obtained from FEM for all considered details including both corrosion and fatigue damage.

In Table 8.10, the differences in damage values are shown between only fatigue and combined Corrosion Fatigue damage.

Detail number	Previous damage number [-]	CF damage number [-]	Difference [-]	Difference [%]
1.1	0.13	0.13	0.00	0.0
1.2	0.49	0.68	+0.19	38.8
2.1	0.00	0.00	0.00	0.0
2.2	0.21	0.88	+0.67	319.0

Table 8.10: Comparison between damage numbers obtained from FEM for only fatigue and Corrosion Fatigue.

Conclusions

First of all, it is observed that for the CF damage numbers also the results for both types of models are consistent. For both types of models, the second detail (1.2 and 2.2, which is trough to cross beam) shows a higher damage number than detail plate to trough (details 1.1 and 2.1).

Then, a comparison can be made between the new and previous damage numbers. It is observed that the two details where the connection between the deck plate and the trough is analyzed (1.1 and 2.1) hardly change at all. This makes sense, as the thickness of the deck plate has not been identified as a critical location in Section 7.4, where thickness reduction due to corrosion should be applied. Since the forces are placed on top of the deck and transferred downwards to ultimately the supports, dimensional changes in cross beams and troughs have little effect on the behavior of the deck plate.

On the other hand, a significant difference is observed in the damage values of the second analyzed details, namely between the cross beam and trough (1.2 and 2.2). The troughs have significantly reduced in thickness due to the application of scenario 8, from t = 5 [mm] to t = 5 - 2 × 0.71 = 3.58 [mm]. This has led to higher stresses around the connection with the cross beam. For the model with a cut-out hole, this resulted in a difference of damage numbers of 38.8%, and for the model without the cut-out hole, a difference of as much as 319.0% was found. Despite these increases, the damage value still remains below 1, so they still meet the required criteria.

If D_{CF} does not satisfy, measures for decreasing the damage number can be taken similarly as for only fatigue. The example is given for detail 2.2:

- The endurance limit for a detail category of 71 [N/mm^2] is 30 [N/mm^2], while the current stress range is 47.1 [N/mm^2]. Therefore, axle load limitation could be a viable solution to possibly give this detail 'endless' lifetime. A new run of the model without heavy loads is required to determine the exact effect of load restrictions.
- The additional service life may be reduced if the number of additional load cycles becomes too high. In the example described, the total allowable number of cycles is 1.0×10^7, while the projected number of future cycles is 8.8×10^6, which is lower and therefore acceptable. If it turns out that more cycles are required than are available, the additional lifetime should be reduced accordingly.

Conclusions

The corrosion damage has been calculated for the Freebrug and for eight different future scenarios. Both types of models meet the requirements, even in the scenario with the most severe corrosion conditions. Furthermore, fatigue damage calculations have been performed. Two governing details are chosen, which are the connections between the deck plate and the trough, as well as the connection between the trough and the cross beam. It turns out that both types of models show alignment in results. Furthermore, all the examined details turn out to currently have a damage value lower than 1 and therefore meet the requirements. Also when a prediction in the future is made of an additional service life of 50 [y], it turns out that the damage numbers are below 1. Finally, the combination of corrosion and fatigue has been assessed for the future scenario of an additional 50 [y]. Compared to the models with only fatigue, the analysed details focusing on the weld between deck plate and the trough do not change in damage number. However, an increase in the damage value of 38.8% is observed for the detail between the trough and the cross beam in the model with a cut-out hole. For the model without a cut-out hole, an increase of even 319.0% in the damage value was observed. Still, all damage values in the future scenario remain below 1 and therefore meet requirements. If the predicted damage number exceeds 1, measures can be taken to reduce the damage, such as shortening the additional service life or applying axle load limitations to reduce stress levels.

9 Model validation

In this chapter, the developed model is validated. This is done by selecting an appropriate mesh to obtain accurate results and desired run times. Then, the assumptions and simplifications made are explained in detail.

9.1. Mesh validation

The FE model will divide the deck into small sections to calculate them individually and link those outcomes in order to achieve the results. A decision must be made on the size of these sections in order to have the desired accuracy.

In other performed studies, it is recommended to use a relatively coarse mesh for the components themselves, while a smaller mesh is suggested for the details (Exterkate, 2024) (Niemi et al., 2018). This finer mesh is not applied to the entire structure to avoid excessively long run times and large storage requirements. The appropriate size of the coarse mesh must be determined to ensure that the accuracy of the model is not compromised. Therefore, different mesh sizes will be run and compared in terms of results and run times.

9.1.1. Unit load to obtain influence lines

To compare the mesh sizes, a unit load is applied to the OSD. This unit load is intended to simulate a force of 1 [kN], representing a traffic load according to the Eurocode, with an area of 0.4 [m] x 0.4 [m]. Thus, $\sigma = F/A = 1/(0.4 * 0.4) = 6.25[kN/m^2]$. The unit load is applied every 0.1 [m] along the deck. A section is made in the trough in the middle of the deck. The influence of the unit load at a specific location can now be represented for this section, which is also known as an influence line. These influence lines will be created for different mesh sizes and compared in order to determine the accuracy of the mesh sizes.

9.1.2. Initial global mesh choices

So first, a mesh size will be determined that can be applied globally. The mesh sizes [mm]x[mm] that have been run are: 300x300, 200x200, 100x100, 50x50, 25x25, 10x10, and 5x5. For the mesh sizes 10x10 and 5x5, the memory of the used laptop is too small to model the entire OSD at this size. To still include these smaller mesh sizes, this smaller mesh size is only applied at the beams that have a significant influence on the obtained stress, which means the 3 troughs around the created section (Exterkate, 2024). For the remaining parts, a 50x50 [mm]x[mm] mesh size has been used. Even with this simplification, it turns out that for a mesh size of 5x5 the memory space is still not big enough. Therefore this mesh size is inappropriate to work with and therefore not taken into consideration further. The results of all influence lines can be seen in Figure 9.1.

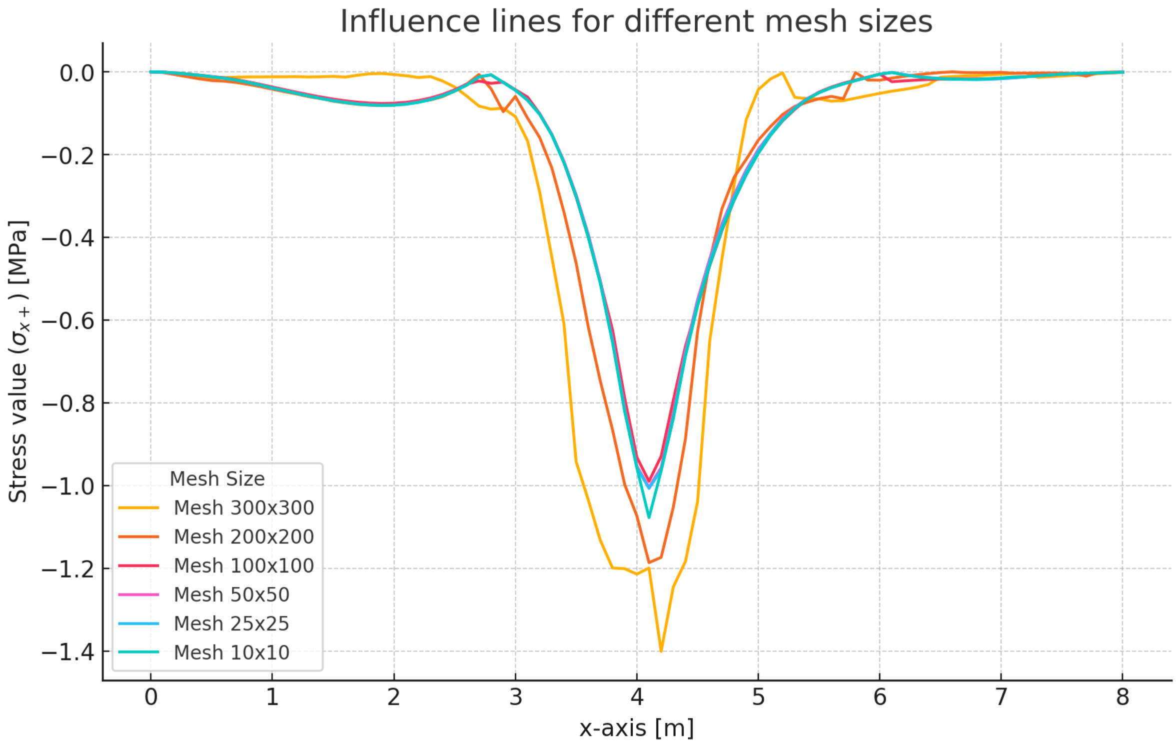


Figure 9.1: Influence lines per mesh size plotted.

In Figure 9.1, it can be seen that the curves for the 50x50, 25x25, and 10x10 mesh sizes overlap and that the bigger mesh sizes do not converge. The 10x10 mesh size has a slightly lower peak, which will be a bit more conservative. The stress difference between the peaks from 25x25 and 10x10 is approximately 7%, calculated as:

$$\frac{\sigma_{10x10} - \sigma_{25x25}}{\sigma_{25x25}} \times 100 \approx \frac{1.077 - 1.007}{1.007} \times 100 \approx 7\%$$

This is quite a significant difference. However, looking at the rest of the curve, the values align and converge with each other. The pink curve is almost invisible because it is similar to the red one. Therefore, it is concluded that all of these three mesh sizes result in accurate results.

9.1.3. Run times

To shorten the run times for each mesh size, a sub-selection has been made of the load cases that need to be run in order to determine the mesh size. For determining the mesh size, it is only important that the unit load cases are run, and these are specifically selected in the run model menu. This way, other load cases, such as self-weight and traffic load, are not run since they are not needed for the mesh check. This results in a reduced runtime of 657 [s] / 98 [s] ≈ 7 [times] for a 50x50 [mm]x[mm] mesh, and a runtime of 797 [s] / 482 ≈ 1.5 [times] for a 25x25 [mm]x[mm] mesh.

In Figure 9.2, it can be observed that the runtime for a 50x50 mesh is significantly smaller than for a 25x25 and a 10x10 mesh. Since these three mesh sizes were found to yield accurate results, it appears that the 50x50 mesh size is the most suitable for this study. This mesh size will be applied globally to the OSD.

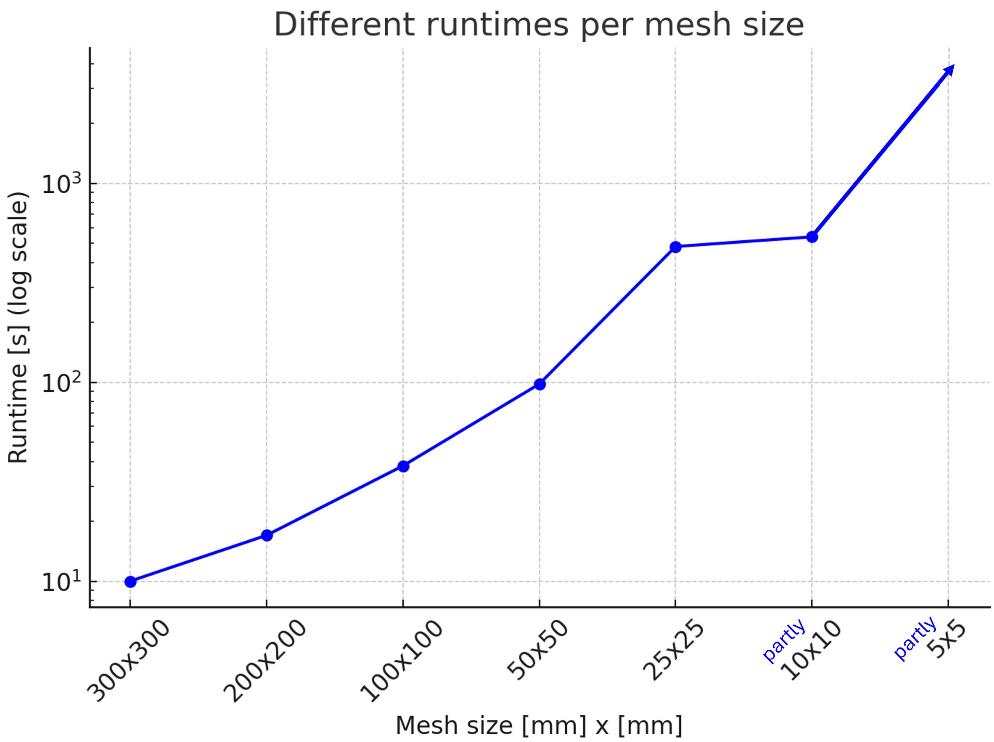


Figure 9.2: Measured run times per mesh size on log scale.

9.1.4. Local mesh refinement

Now that the global mesh has been decided, local mesh refinement will be applied around the details by designating mesh regions, also known as influence areas or 'Radius' in SCIA Engineer. Based on recommendations from experts at Sweco, the local mesh size will be the thickness of the plate from which the stress is to be read. For the troughs holds t = 5 [mm], so this is chosen as the mesh size. Furthermore, the size of the influence area of the local mesh needs to be determined. To do this, different values for radii will be run, as shown in Table 9.1. The larger the radius, the bigger the size of the finer the mesh, which results in higher accuracy of results, but also longer runtime. To gain insight into the difference of the values, a sensitivity analysis will be performed. The obtained results will be compared to the first run, which uses the smallest mesh size and largest influence area, providing the highest accuracy and the longest runtime.

Mesh size [mm]x[mm]	Radius [m]	σ_x^+ [MPa]	Difference σ_x^+ compared to first
5x5	1.0	0.4775	-
5x5	0.5	0.4743	-0.67%
5x5	0.2	0.4739	-0.75%
5x5	0.1	0.4706	-1.45%
5x5	0.05	0.4705	-1.47%
10x10	1.0	0.4779	+0.08%
10x10	0.5	0.4750	-0.52%
10x10	0.2	0.4705	-1.47%
10x10	0.1	0.4706	-1.45%
10x10	0.05	0.4705	-1.47%

Table 9.1: Sensitivity analysis of stresses for different influence regions.

According to Table 9.1, as the influence area decreases, the stress difference increases, reaching a maximum of 1.47%. More accurate results are observed with a radius of 0.5 [m], as it yields reliable results for both the 5 [mm] and 10 [mm] mesh sizes.

In short, a global mesh size of 50x50 [mm]x[mm] is chosen, and locally around the analyzed detail, a mesh size is selected with the plate thickness x the plate thickness [mm]x[mm], with a radius of 0.5 [m].

9.2. Simplifications

To create the model, several aspects have been simplified compared to reality. This is done to ensure that the model can be created and used within the intended timeframe of this thesis. Simplifications affect the outcome and reliability of the model, which is why they are further explained here. What these simplifications mean for the conclusions drawn will be elaborated in the Discussion, which is Chapter 13.

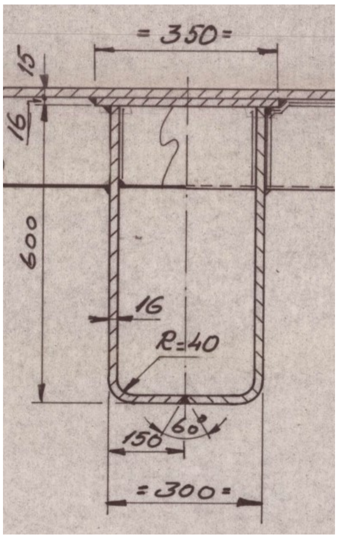
9.2.1. Neglecting arc radius (R)

The drawings of the cross beams and troughs can be seen in, respectively, Figures 9.3a and 9.3b. These figures show that both components have round 'connection points' in reality, by using an arc. For the cross beam, R = 40 [m], and for the trough, R = 30 [m]. These arc radii are not included in the model, instead the plates are connected with an angle, as shown in Figure 7.1 in Section 7.2. The angle of the cross beam is $90°$, and the angle of the trough denoted as 'α' with respect to the z-axis, is chosen to match the drawing:

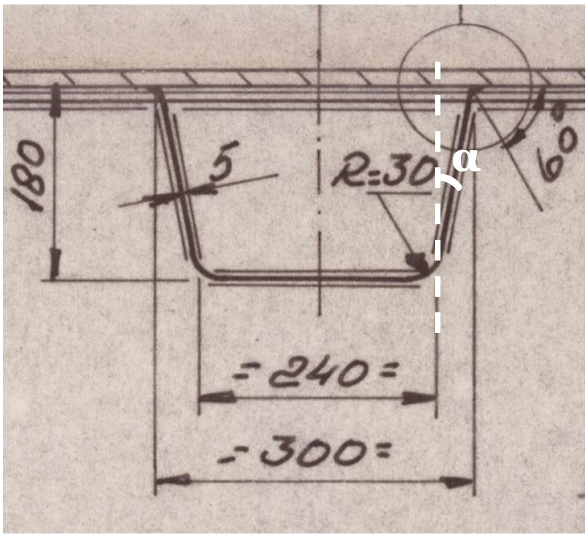
opposite side $= \frac{300-240}{2} = 30$ [mm]
adjacent side $= 180$ [mm]
$\alpha = \tan^{-1}\left(\frac{30}{180}\right) \approx 10$ [°]

It is necessary to make this simplification, because for an OSD, it is essential that the profiles are made from 2D material so that the force transfer can be considered in the 3D direction. The existing U-profiles in SCIA Engineer that do include an arc radius are only 1D profiles. 1D profiles can not be connected to 2D plates, and thus, the force transfer would not be correctly represented in the OSD. In the combination of 1D profiles with 2D plates, the forces applied to the deck would only lead to stresses in the deck itself, and not transfer further, which is incorrect. To overcome this issue, the profiles are self-assembled from 2D plates and connected at the angles that most closely match the drawings.

For an even more accurate analysis, a so-called 'shell' 2D element could be applied in SCIA Engineer at the small locations of the cross beams and troughs where the horizontal plates are connected to the vertical/diagonal plates. The arc radii would then be created using small 'shell' elements. In practice, this is not modeled in such a way because it is a time-consuming task and irrelevant for this thesis as the stress distribution in the OSD is not likely to change much.



(a) Drawing of cross beam obtained from dossier of Sweco.



(b) Drawing of trough obtained from dossier of Sweco.

Figure 9.3: Drawings of cross beam and troughs obtained from the dossier of Sweco.

9.2.2. Neglecting specific loads

In the model, three types of loads are modeled, namely the self-weight, the cambering of the steel, and the traffic load. In reality, the deck will be subjected to more types of loads. One of the loads that will be neglected, is the temperature load. Temperature load can be relatively easily modeled with SCIA Engineer by inputting the temperature differences in the deck. For this deck, it is assumed that there are small temperature fluctuations, so temperature does not play a relevant role in the stress state.

Additionally, braking and acceleration forces can also be included in the analysis of the deck. These loads will contribute to a different stress distribution on the deck and can also be governing. However, there is no information available on these forces, and these are also more relevant for larger bridges with higher traffic intensities and higher speeds. For the deck in this study, a simplified version is modeled, as such a complex model is not necessary to draw the intended conclusions from the model regarding reuse.

Wind load is also disregarded in this study. Wind load certainly plays a role in the assessment of a component for strength and stiffness and can even contribute significantly. However, this thesis focuses on the aspect of reuse. For each type of reuse application, the wind load will be different, and at this stage of the research, it is not possible to determine how large the wind load will be and which direction is dominant. Therefore, it is recommended to include wind in a later stage in the structural assessments, and for this reason, it will be disregarded in this research.

9.2.3. Neglecting the lateral steel rods

In the design drawings of the Sweco file, it can be seen that the bridge has a large hinge point and can rotate around this point when it needs to open. Additionally, there are also steel rods at 2 locations along each edge of the deck that provide stability during lifting, see Figure 9.4. The Freebrug is currently no longer operational as a bascule bridge and is only used as a fixed bridge. Therefore the forces within the bridge will always be transferred downward from the deck to the foundation, and it is unlikely that they will be transferred upward into the lateral steel rods. Therefore, it is assumed that these rods will not contribute to force transfer and are purely functional for opening and closing the bridge. Therefore for this study, it is not necessary to model these rods to the OSD.

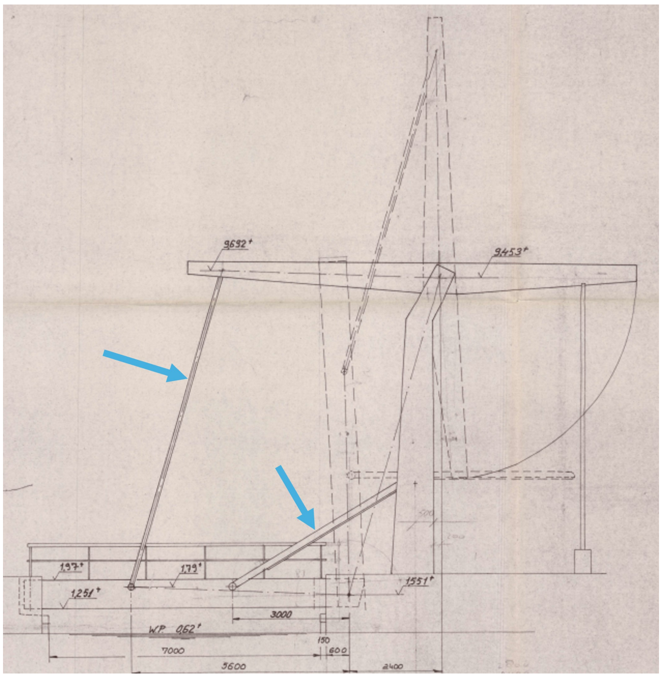
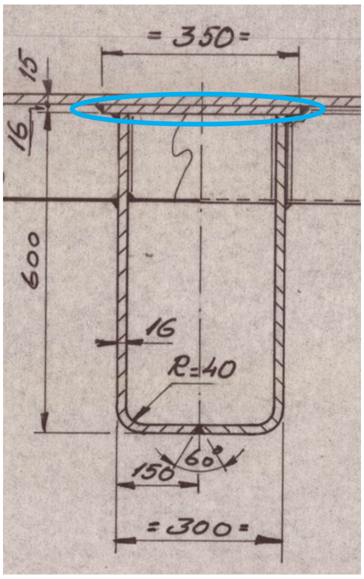


Figure 9.4: Overview Freebrug obtained from dossier of Sweco, lateral steel rods shown with blue arrows.

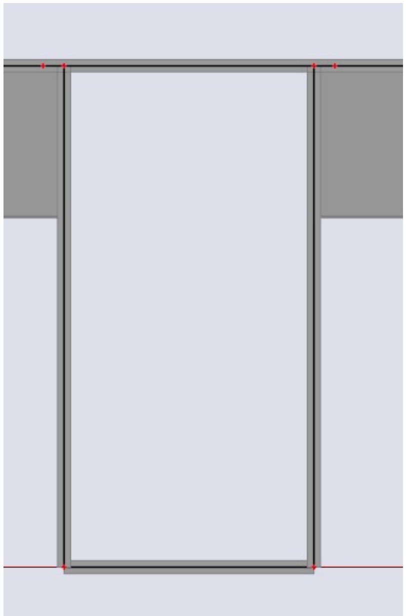
9.2.4. Neglecting upper plate cross beam

A simplification was made by assuming that the cross beam profile consists of three plates forming a U-profile, as shown in Figure 9.5, instead of also including the upper plate (as shown with the blue circle). Due to this simplification, the model lacks some thickness at these locations compared to the actual drawings, resulting in a bit reduced stiffness and strength. This simplification was made because modeling a fixed connection between two overlapping plates is a complex process in SCIA Engineer. To achieve this, welds would need to be modeled, which is a time-consuming and detailed task. An alternative solution would be to locally define a region with increased thickness or stiffness. These adjustments are certainly important if the bridge does not meet strength requirements.

Moreover, the method of placing and welding a top plate onto a U-profile is no longer used in new construction. Nowadays, the U-profile is directly welded to the deck plate, meaning that the fourth plate (upper plate) is no longer present. So for a more general design approach of an OSD, it is therefore also beneficial to exclude this upper fourth plate from the model.



(a) Drawing of cross beam obtained from dossier of Sweco (blue circle shows neglected upper plate).



(b) Modelling of cross beam in SCIA Engineer.

Figure 9.5: Comparison of drawing and cross beam in model.

9.3. Assumptions

9.3.1. Profiles of plate material

As mentioned in Section 7.2, the profiles from the deck are modeled by using separate plates, and the deck is also a 2D plate. This is done despite the fact that there exists an option in SCIA Engineer to directly choose pre-programmed profiles (HE700A, U profiles, etc.) and their corresponding properties. This option has not been used, because these pre-programmed profiles are 1D elements. One disadvantage of this is that a 1D element can not be connected to a 2D element, which would mean that all loads applied to the 2D deck would not be transferred. In practice, for modeling an OSD, a plate model is therefore developed. All profiles have been manually created from plates with interconnecting welds as rigid links, and the corresponding properties of the respective sub-component have been added for each plate.

9.3.2. Welds as rigid links

Another assumption and simplification made in the model is the modeling of the welds as rigid links. This has been done by creating connection points, or so-called 'nodes', at the locations where plates meet. By making the coordinates of these points exactly the same for both plates, a rigid link is automatically created.

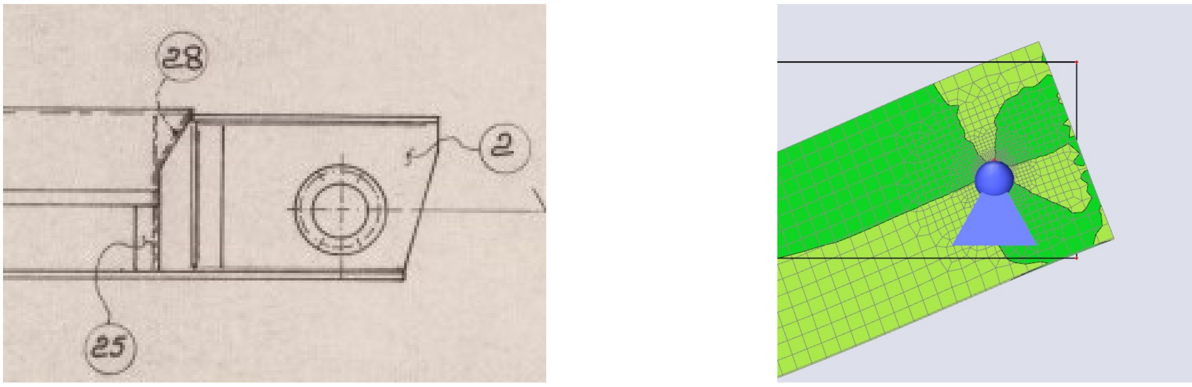
The welds may be assumed as rigid links, because this allows for a simple way to simulate the interaction between the plates. The forces will be transferred from plate to plate through the rigid links and ultimately to the supports. The model focuses on the force transfer and stress distribution in the deck, which can be effectively visualized in this way.

One downside of this method is that modeling the welds as rigid links implicitly assumes that the welds will not fail in strength. Besides to that, the welds are modeled too stiff compared to reality, and local stresses and deformations will not occur as easily. This assumption is also commonly done in practice, but should be kept in mind when drawing conclusions.

9.3.3. Support conditions

As described in Section 7.2, the bridge is supported on one side with a hinge, allowing degrees of freedom in the three rotational directions (Rx, Ry, and Rz). The other side of the deck is supported as sliding, meaning it is rigid only in the z-direction. The assumption of these supports is based on the fact that it is originally a bascule bridge (even though it no longer opens and closes). Therefore, one side is by definition hinged, while the other side is assumed to be roller-supported, as it could have moved in the z-direction in the past.

The actual location of the pivot point can be seen in Figure 9.6a. It is shown where it is positioned in the main girder and the fact that the hinging point is relatively large. In SCIA Engineer, this hinge is modeled as closely as possible, as shown in Figure 9.6b. However, this is an approximation since the support in SCIA Engineer is placed at a very small surface, unlike the reality where the force is distributed over the entire hinge. As a result, significant peak stresses appear around this node of the support. To avoid local stress disturbances, the decision was made to model the support at the end of the main beam. In principle, both modeling approaches will not affect the results, as none of the required stresses will be read near the support. The critical areas in the deck and the details where stresses are determined are further along the deck, so the influence of the local peak stresses has already dissipated.



(a) Drawing of side view of the pivot point from dossier of Sweco.

(b) Pivot point side view of the deck in SCIA Engineer.

Figure 9.6: Comparison of hinge in model and hinge in drawings.

Conclusions

A mesh validation is performed by plotting influence lines at different mesh sizes. The most suitable global mesh size is chosen based on a balance between accuracy and run times, which is 50x50 [mm]x[mm]. Locally, around the analyzed detail, a finer mesh size is applied namely the plate thickness x plate thickness [mm]x[mm], with a radius of 0.5 [m]. In addition, the simplifications and assumptions made by the researcher have been explained in detail. These should be kept in mind when drawing conclusions based on the model.

10

Design guideline

This chapter outlines the procedure that should be followed to determine the reuse potential for OSDs. It consists of three steps that should be performed subsequently. Furthermore, the applicability of the guideline is described.

Summary of steps in overview

The three steps that need to be carried out are shown in Figure 10.1. The corresponding goal of each step is also indicated. A more detailed explanation is provided below per step.

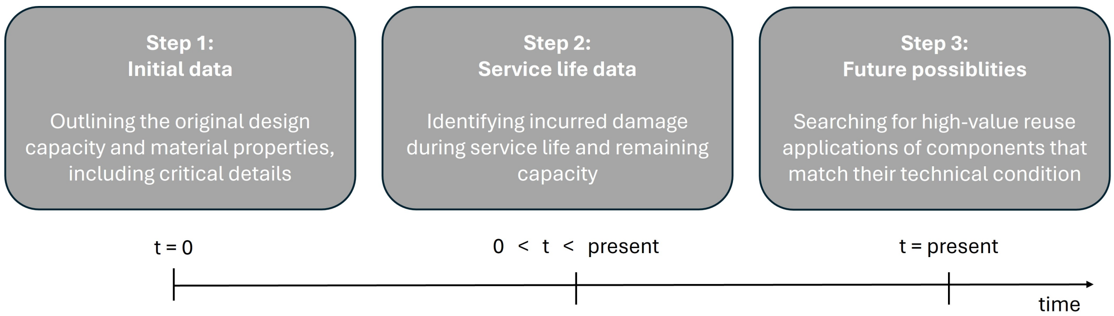


Figure 10.1: Developed schematization of steps supported with a timeline.

10.1. Step 1: Initial data

Every construction component should have a so-called material passport. The purpose of this passport is to identify components, assign them a unique code, and document their condition.

First of all, the following information needs to be checked (CEN-members, 2023):

- The steel is produced after 1955.
- The donor structure is located in the Netherlands.
- The steel has not been plastically deformed in an uncontrolled manner.

Secondly, reused steel will require different levels of quality depending on its specific application. Therefore, consequence classes are distinguished. The requirements for reliability and quality of information vary among these different classes accordingly. The application areas are categorized into three research classes and can be found in Table 10.1. CC1 includes, for example, simple commercial buildings, industrial buildings (1 or 2 floors), and standard single-family homes. CC2 includes bridges, residential buildings up to 70 meters tall, public buildings like libraries and schools. CC3 includes high-rise buildings, grandstands, and hospitals.

Research Class	Application area
1	Consequence Classes CC1a and CC1b (limited social consequences)
2	Consequence Classes from CC1a to CC2 (fair social consequences)
3	All Consequence Classes (major social consequences)

Table 10.1: Definition of different classes (CEN-members, 2023).

Furthermore, Table 10.2 specifies the minimal quality requirements to allow for a steel profile to be assigned to a certain research class.

Visual inspection	Research Class 1	Research Class 2	Research Class 3
Damage, repair?	Allowed	Allowed	Not allowed
Loss of cross-section? [a]	Allowed	Allowed	Not allowed

[a] This applies, for example, when a section of the steel profile has been cut.

Table 10.2: Requirements for visual inspection based on different classes (CEN-members, 2023).

Thirdly, the next step involves documenting the known information about the component to be reused. This part of the material passport of the component is also referred to as 'keuringsdocument' in Dutch.

The 'keuringsdocument' should contain at least the following information:

- **Justification of inspection units:** The structure must be divided into logical inspection units, with each assigned a unique code. The profiles should be sorted in inspection units of a maximum of 20 tonnes, and their application in the donor structure (type of structural application, location in the structure, conditions; inside or outside, loading.)

- **Original documentation of the donor structure:** See Table 10.3 and explanation below.

Status	Document
1	Inspection documents, CE marking or Declaration of Performance (DoP)
2	Manufacturing drawing
3	Execution-ready design calculation
4	Final design drawing/Final design calculation
5	Preliminary design drawing/Preliminary design calculation

Table 10.3: Hierarchy of archive information about the donor structure (CEN-members, 2023).

Table 10.3 illustrates that different statuses correspond to different documents, which each have their own level of reliability of information. Currently, in a lot of design cases proper information regarding drawings or inspection documents is lacking. Buildings and bridges built after World War II commonly do not have proper documentation and this would limit their reuse potential if the material passport must be completed. Therefore, the lower bound approach exists. This approach can be found in Appendix F and describes the minimal material properties that may be assumed for tensile strength, yield strength, fracture toughness and maximum carbon equivalent (CEV). The latter value is relevant for welding. In this way, also steel components with lacking documentation have the potential to be reused.

- **Documentation of material properties:** See Table 10.4. The term 'Regular design norms' refers to any applicable Eurocode, for example, NEN-EN 1993-1-1 can be used.

Material properties	Research Class 1	Research Class 2	Research Class 3
Material properties	On the basis of information (archive) from donor structure or Appendix F or through testing		
Ductility requirements (deformation requirements)	OK if steel grade can be found in regular design norms		
Fracture toughness	On the basis of information (archive) or Appendix F		
Properties in thickness direction	Can be found in regular design norm		
Tolerances	Can be found in Appendix G		
Design values of material properties	On the basis of regular design norms		
Weldability	1 destructive test or Appendix F	1 destructive test	3 destructive tests

Table 10.4: Guideline for determining material properties for each research class (CEN-members, 2023).

- **Justification of type of preservation:** The type and condition of any preservation measures must be recorded, if known. Furthermore, suspicions of toxic substances such as lead, chromium-6, and other heavy metals must be mentioned. If research is conducted and toxic substances are found, it can be decided to blast the steel or to use it in an application where the substances do not pose a risk (CEN-members, 2023).

- **Identification of critical locations**: The critical areas of the structure immediately after delivery must be identified. This can be determined based on calculations already included in the documentation of the donor structure. If such documents are not available, an FE model, hand calculations or expert judgement, can be used to identify the critical locations. All the applied loads should be taken into consideration as well as how they are combined into cases and combinations. An example can be found in Section 7.3. A list of critical stress locations is required for the damage assessment in the next step.

10.2. Step 2: Service life data

Now that the necessary basic information after delivery has been written down, it can be supplemented with details about what the components have experienced throughout their service life.

10.2.1. Monitoring reports

In Research Class 1 and Research Class 2, components are allowed to have damage resulting from their initial service life. Therefore, the next step in the process is to assess the current condition of the components and, if possible, the deterioration of the material over time. This can be done based on maintenance reports, monitoring and thorough visual inspections. An example of criteria for a visual inspection is given in Table 10.5. It should be as detailed as possible.

Attribute	Description	Common examples
Object number	Unique identification code of the bridge	-
Object name	Official name of the bridge	-
X coordinate	Geographic X coordinate	-
Y coordinate	Geographic Y coordinate	-
Year of construction	Year the bridge was built	-
Bridge type	General classification of the bridge	Movable, fixed, cable-stayed, suspension
Subcategory	Specific type within the general category	Bascule bridge, swing bridge, arch bridge
Parts	Major structural elements	Load-bearing structure, railing, foundation, deck, bearings
Components	Specific elements within a part	Protective layer, drive system, counterweight, cross beam, expansion joint
Material	Type of material used	Steel, concrete, wood, asphalt, rubber, thermoplastics
Condition score	Rating based on expert assessment	1 - Excellent to 6 - Very bad
Initial lifespan	Estimated design lifespan	50 years, 75 years
Factor	Degradation rate factor	Score 1 = 0.10, Score 2 = 0.30, etc.
Reduction in years	Years deducted due to degradation	Initial lifespan $\times$ Factor
Remaining lifespan	Estimated remaining lifespan	Initial lifespan $-$ Reduction in years
Defect	Common types of failures	Corrosion, cracks, spalling, missing components
Damage description	Details of observed damage	Wood rot, fire damage, exposed reinforcement
Damage location	Specific area of damage	Deck underside, central pier, abutment
Damage size	Measurement of damage extent	1m^2, 5cm crack, 60% affected
Cause of damage	Reason for deterioration	Traffic load, aging, missing preservation, fatigue failure
Damage aspect	Classification based on impact	Safety, durability, functionality
Expected damage development	Predicted future damage	Expansion of cracks, increased corrosion, risk of instability

Table 10.5: Inspection document of present damage.

A visual inspection can provide an initial impression of the bridge's condition. However, as explained, not all damage is visible to the naked eye, so calculations will also need to be carried out to determine the actual damage present in the steel.

10.2.2. Corrosion damage

The assessment for corrosion can be done by gathering the following information and filling in the formulas:

- **Justification of corrosivity class**: Corrosion is strongly dependent on many factors in the environment, such as temperature, humidity, and the presence of corrosive substances. This is summarized in 6 so-called 'corrosivity categories', with which the estimation of corrosion attack values for metals and alloys exposed to natural outdoor atmospheres can be made (CEN-members, 2012a). There must be chosen to which corrosivity class the structure is subjected. The subdivision of these categories can be found in Appendix B.
- **Determination of previous exposure time**: The duration of exposure to corrosion for the structure must be determined. This can be done based on the year in which the structure is built, which is documented in Step 1.
- **Definition of future corrosion scenarios (S_i)**: The potential reuse application depends on the extent of corrosion, and therefore different scenarios are initiated. These scenarios should involve varying corrosivity classes and durations of additional service life (e.g., 15 [y] extra or 25 [y] extra, etc.). This allows variation in possible environments and potential applications to gain insight into what is and is not feasible, and possibly to adapt the application accordingly.

- **Calculation of total attack (D_C)**: The various formulas to calculate the corrosion damage (attack) for different time periods is provided in Table 10.6. For every scenario the total corrosion attack can now be calculated.

A distinction is made between duration types of corrosion, namely the initial period, which is the first 10 [y], the steady-state corrosion for the years thereafter, and the long term estimation. This is done because the development of corrosion is not constant over the exposure time. For most metals, the corrosion rate decreases over time, because the corrosion products that form on the surface counteract further formation.

Time period [y]	Elaboration	Formula
0 – 10	Initial period	$D_C = r_{\text{corr}} \cdot t^b$
10 – 20	Steady-state	$D_C = r_{\text{corr}} \cdot t^b$
> 20	Long term	$D_C(t > 20) = r_{\text{corr}} \left[20^b + b \cdot 20^{(b-1)} \cdot (t - 20)\right]$

Table 10.6: Overview of different corrosion periods with corresponding formulas (CEN-members, 2012b).

where

- D_C = total attack as mass loss per unit area [g/(m^2·a)]
- t = exposure time [y]
- r_{corr} = corrosion rate for the first year [g/(m^2·a)], see Appendix C (CEN-members, 2012b)
- b = metal-environment-specific time exponent (usually < 1)

And this time exponent 'b' can be filled in in two ways, namely with B1 and B2 (CEN-members, 2012a).

- B1 values represent the average time component
- B2 values represent the upper limit of corrosion attack (two standard deviation additions are done)

Values for B1 and B2 can be found in Appendix D. By filling in the 'b' value and time the total damage attack can be determined up to 100 [y] of corrosion.

- **Application of calculated attack**: The calculated total attack per scenario can be translated into a thickness reduction using Formula 10.1. These thickness reductions can be applied to the profiles at the critical locations identified in Step 1 (as corrosion at these points will reduce the resistance of the cross-section and consequently increase the stress). An example of such an application of thickness reduction can be seen in Figure 10.2 in FE model, but this can also be done manually using hand calculations if no software is used.

$$\Delta t = \frac{D_C}{\rho} \tag{10.1}$$

where

- Δt = thickness reduction [mm]

- D_C = corrosion attack in [g/m^2]
- ρ = density of steel (≈ 7850 [kg/m^3] $= 7.85$ [g/cm^3]).

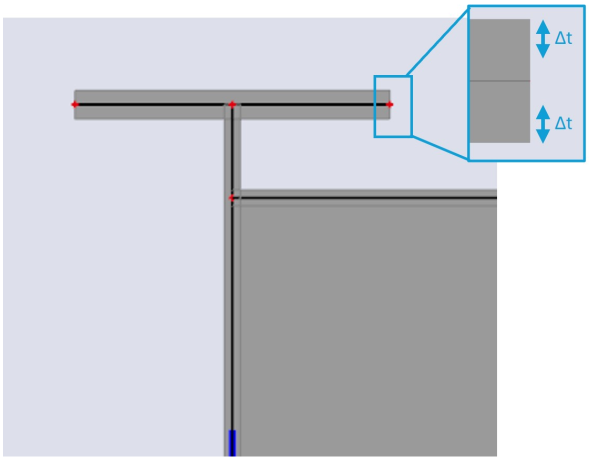


Figure 10.2: Example of thickness reduction shown on a profile.

- **Verification of stresses**: The structure with adjusted profiles can now be verified per different scenario using stress verifications.

$\rightarrow$ **The chosen values per scenario and the corresponding results for stress verification must be carried over to Step 3.**

10.2.3. Fatigue damage

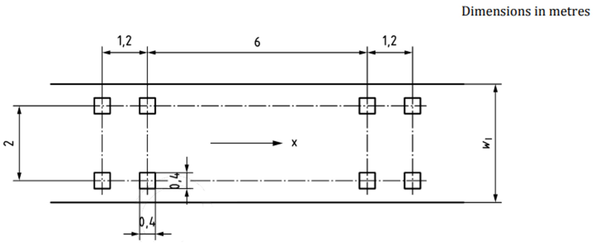
The OSD should also be assessed for fatigue. The assessment for fatigue can be done by gathering the following information and filling in the formulas:

- **Calculation of loading history**: First of all, the loading history of the bridge must be known. If this has not been measured, an estimate can be made of the number of vehicles over the years based on the year the structure is built as is identified in Step 1.

- **Choice of Fatigue Load Model**: Next, a decision must be made regarding which Fatigue Load Model (FLM) will be used to perform the verifications. For small regional bridges, FLM3 is considered sufficient and for larger provincial bridges, FLM4 is recommended.

Only FLM3 is elaborated in detail in this thesis and will therefore be further explained here.

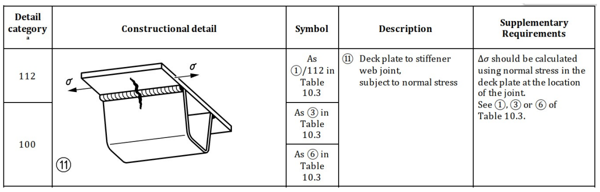
FLM3 is represented by four axle loads, each with two identical wheels. A schematic representation of FLM3 can be found in Figure 10.3. This model uses a single vehicle instead of a range of different vehicles and multiple configurations. The vehicle is represented by an axle load of 120 [kN]. These axle loads must be applied at every meter along the bridge to simulate all possible loading positions. An example of such a loading situation is shown in Section 8.2.1.



Key
W1 Lane width
X Bridge lane direction

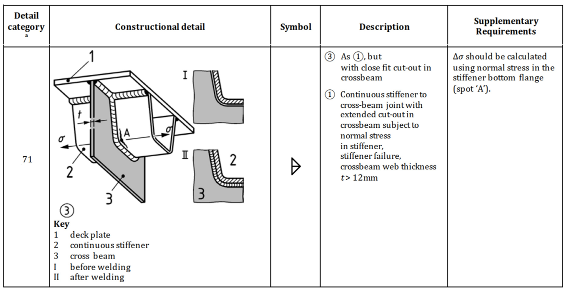
Figure 10.3: Fatigue load model 3 (CEN-members, 2021b).

- **Determination of most governing types of details**: Not all parts of the deck will experience the same amount of fatigue damage. Welds will contain local peak stresses and are therefore susceptible to fatigue cracks. The governing details in OSDs that should at least be assessed for fatigue are shown in Figure 10.4 and Figure 10.5. These are the welds between deck and trough and welds between trough and cross beam. In these figures, which specific sub-components and corresponding directions that need to be evaluated are indicated with arrows ($\rightarrow$).



Detail category [a]	Constructional detail	Symbol	Description	Supplementary Requirements
112	⑪	As ①/112 in Table 10.3	⑪ Deck plate to stiffener web joint, subject to normal stress	$\Delta\sigma$ should be calculated using normal stress in the deck plate at the location of the joint. See ①, ③ or ⑥ of Table 10.3.
100		As ③ in Table 10.3		
		As ⑥ in Table 10.3		

Figure 10.4: Detail category for trough to deck weld according to NEN-EN 1993-1-9-2024 (CEN-members, 2024).



Detail category [a]	Constructional detail	Symbol	Description	Supplementary Requirements
71	③ Key 1 deck plate 2 continuous stiffener 3 cross beam I before welding II after welding		③ As ①, but with close fit cut-out in crossbeam ① Continuous stiffener to cross-beam joint with extended cut-out in crossbeam subject to normal stress in stiffener, stiffener failure, crossbeam web thickness t > 12mm	$\Delta\sigma$ should be calculated using normal stress in the stiffener bottom flange (spot 'A').

Figure 10.5: Detail category for continuous trough to cross beam joint according to NEN-EN 1993-1-9-2024 (CEN-members, 2024).

- **Determination of most governing detail of each type**: By applying FLM3 to the deck, the stresses in the deck can be read. The detail of each type with the highest stress range can now be identified and these governing details are then used further for the fatigue verification. To determine the stress range, the absolute difference between stresses must be calculated, as shown in Formula 10.2. The stress range for the governing details should be determined two distances from the weld, namely at 10 [mm] and at 15 [mm]. The average value of these two should be used further in the calculation. Since the values are dependent on the mesh size, it is important to take two measurements and calculate their average.

$$\Delta\sigma = |\sigma_{\text{FLM,max}} - \sigma_{\text{FLM,min}}| \tag{10.2}$$

- **Calculation of damage numbers**: Now the damage can be calculated for the chosen details. The S-N curve can be used to determine the number of cycles (N) corresponding to the calculated $\Delta\sigma$. This is then compared to the number of cycles that have already occurred on the bridge per slow lane. The damage factor due to fatigue is then determined using Formula 10.3, also known as the Palmgren-Miner rule.

$$D_F = \sum \frac{N_{\text{pas}}}{N_{\text{SN curve}}} \tag{10.3}$$

The structure currently meets the requirement if $D_F < 1$. However, this only applies to the current condition, and the damage factor D_F will increase with prolonged future use.

- **Prediction of future purposes**: To assess whether the component remains suitable for reuse, the fatigue performance under an intended future scenario should be evaluated. Based on the estimated number of future load cycles (N_{fut}) and the fatigue capacity from the S-N curve ($N_{\text{SN curve}}$), the expected damage factor D_F can be read. If $D_F < 1$, the detail is acceptable for this reuse scenario. Alternatively, the total allowable number of remaining cycles ($N_{remaining}$) under the same loading conditions can also be estimated directly from the S-N curve with Formula 10.4.

$$N_{remaining} = N_{SNcurve} - N_{pas} \tag{10.4}$$

→ The values of the chosen scenario and corresponding results for remaining service life must be carried over to Step 3.

10.2.4. Corrosion Fatigue damage

The combination of corrosion and fatigue should also be taken into account. This means that both procedures are combined: a thickness reduction is applied to the cross-section, and at least the two selected fatigue details are evaluated. The same intended future scenario (S_i) should be used consistently in both damage procedures. For example, if an additional service life of 50 [y] is assumed for corrosion, the same 50 years must also be used to determine the number of heavy vehicle passages (N_{pas}) when calculating fatigue damage.

- **Calculation of damage numbers and future purposes**: The OSD is again evaluated using Formula 10.3 and meets the requirement if $D_{CF} < 1$.

→ The values of the chosen scenario and corresponding results for remaining service life must be carried over to Step 3.

Reflection on Step 2

The three described types of damage are the most governing failure mechanisms for steel bridge components and should be assessed at a minimum. Standardizing this process will help streamline evaluations, but it does not rule out the possibility of other failure mechanisms. Therefore, careful assessment is essential. In addition to visual inspections and calculations, it is recommended to do regularly monitoring and use NDT techniques, such as ultrasonic or magnetic particle testing, to detect potential cracks or defects.

10.3. Step 3: Future possibilities

In summary, Step 1 identifies the information that is required to be able to carry out Step 2. Based on Step 2, it can be concluded what the current condition of the steel is by calculating the damage accumulated during the structure's service life.

This allows for a translation to Step 3. Based on the identified damage, certain reuse applications may be feasible while others are not. Among these various reuse applications, some will retain more value than others. As described in the literature review in Section 3.1, the goal is to preserve as much value as possible.

10.3.1. Corrosion routes

In Section 8.1, a case study is carried out for an OSD subjected to corrosion. This analysis shows that corrosion scenarios depend on several aspects:

- Exposure time (can be varied)
- Corrosivity class (can be varied)
- Applied loads (can be varied)
- Resistance of profiles (can not be varied, work with what is available)

Additionally, Step 2 determined under which corrosion scenarios the deck meets the stress requirements and under which it does not. If it turns out that a desired scenario does not comply, it is possible to adjust a certain aspect of the list above and recalculate to see whether it then meets the requirements. The consequences of such an adjustment on the reuse potential can be seen in Figure 10.6 and a more detailed explanation is given below.

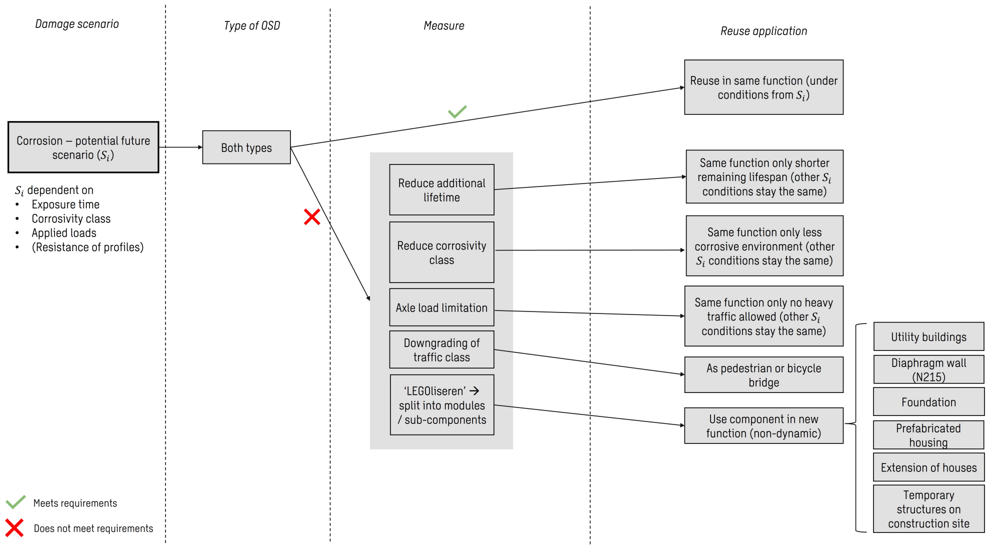


Figure 10.6: Developed overview of corrosion scenario resulting in possible future applications.

On the left, a possible future corrosion scenario (S_i) for the deck is depicted. Based on the case study in Section 8.1, it is concluded that with regard to corrosion, there is no difference in the expected outcomes between an OSD with cut-out holes and without cut-out holes. So the possible future scenario is connected to both types of OSDs, and no distinction is made.

Then further to the right, the 'Measure' column shows possible technical measures that can be taken. A green check mark (✓) indicates that the intended scenario meets the requirements, and no measure is necessary. A red cross (X) signals insufficient performance. In this case a measure should be taken and the rightmost column shows the effect of a particular measure for the reuse application. In short, this diagram can serve as an indication, providing direction and guidance on whether a certain reuse application is viable or not. → **An example illustrating the application of the overview is given for Corrosion Fatigue in Subsection 10.3.4.**

10.3.2. Fatigue routes

Additionally, in the case study, the OSD is also subjected to fatigue. From Section 8.2, it was determined that the following aspects exert influence:

- Amount of passing heavy traffic (number of cycles) (can be varied)
- Type of heavy vehicles (can be varied)
- Detail category (can not be varied, work with what is available)

Besides to that, in Step 2 the fatigue damage numbers are determined, along with the remaining service life under identical loading conditions. If it turns out that the remaining life is insufficient for the intended future scenario, one of the influencing aspects can be adjusted. The consequences of such an adjustment on the reuse application are shown in Figure 10.7 and a detailed explanation is given below.

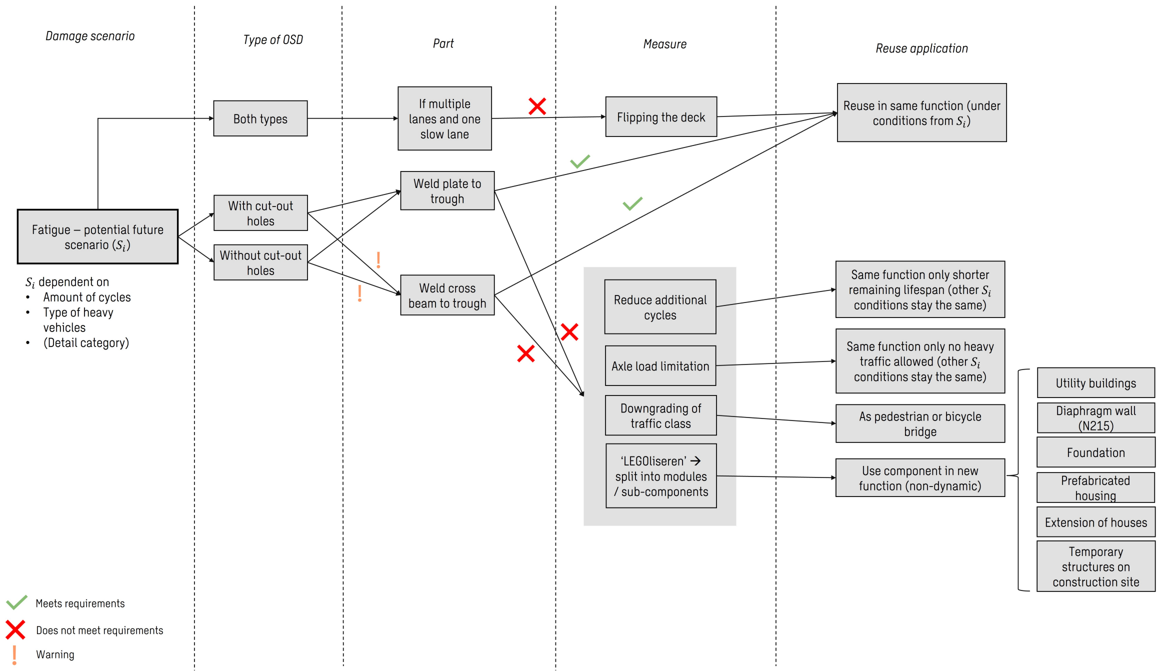


Figure 10.7: Developed overview of fatigue scenario resulting in possible future applications.

On the left, a possible future fatigue scenario (S_i) for the deck is shown. Based on the case study in Section 8.2, it is found that for both types of OSDs the most critical detail is the weld between cross beam and trough. It is therefore possible that a scenario arises in which the weld between the top plate and the trough is still in good enough condition to be reused, and that the weld between the cross beam and the trough is not OK. In such a case, an evaluation would be needed to determine whether partial disassembly of the OSD retains more value than full separation. Therefore, attention is needed and this is indicated by a warning symbol (!).

Again, even further to the right, the 'Measure' column shows possible technical measures that can be taken. A green check mark (✓) indicates that the intended scenario meets the requirements, and no measure is necessary. A red cross (X) signals insufficient performance. Then a measure should be taken and the rightmost column shows the effect of a particular measure for the reuse application. One such measure is 'flipping the deck', which means rotating the deck around its vertical (z) axis in plan view, effectively swapping the fast and slow lanes. This can be relevant when fatigue damage differs across the width of the deck. In short, this overview serves mainly as a first indication which provides guidance on which reuse option is viable and not. → **An example illustrating the application of the overview is given for Corrosion Fatigue in Subsection 10.3.4.**

10.3.3. Corrosion Fatigue routes

Finally, in the case study, the OSD is also subjected to the combined effect of Corrosion Fatigue. The influencing factors in this regard are:

- Exposure time/amount of cycles (can be varied)
- Corrosivity class (can be varied)
- Applied loads/type of heavy vehicles (can be varied)
- Resistance of profiles (can not be varied, work with what is available)
- Detail category (can not be varied, work with what is available)

Furthermore, in Step 2 the Corrosion Fatigue damage numbers and the remaining service life under identical conditions are determined. If this remaining life turns out to be insufficient for the intended future scenario, one or more influencing factors can be adjusted. The potential consequences of such adjustments for the reuse application are shown in Figure 10.8 and a detailed explanation is given below.

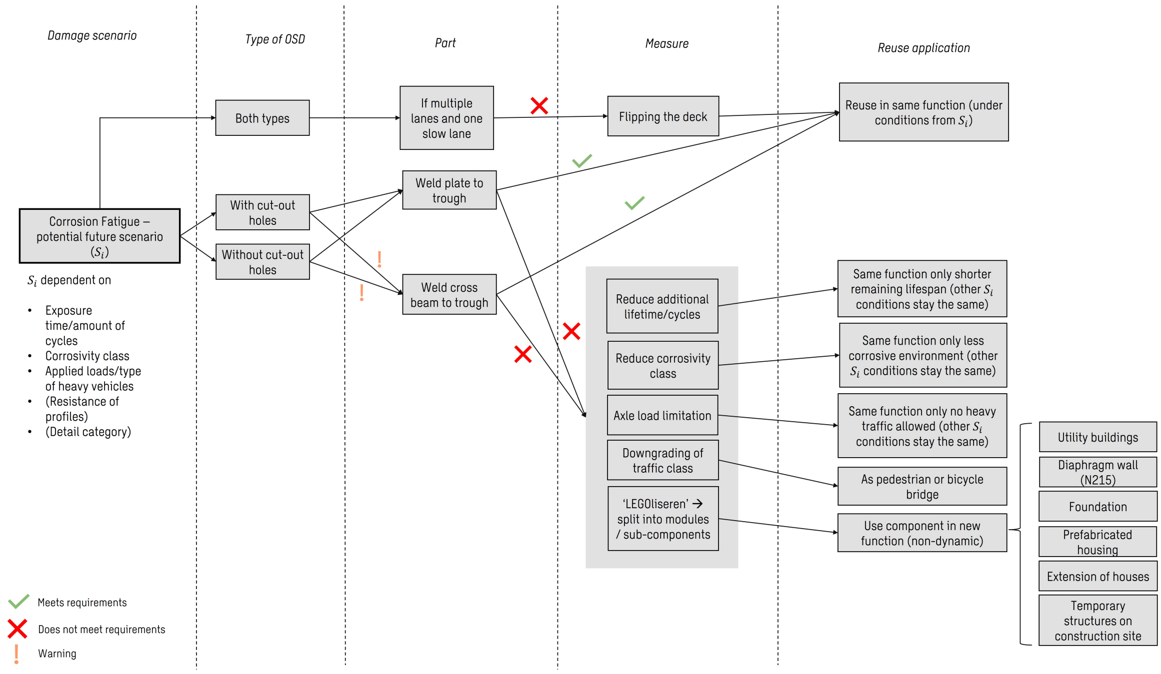


Figure 10.8: Developed overview of Corrosion Fatigue scenario resulting in possible future applications.

Figure 10.8 visualizes a possible Corrosion Fatigue scenario (S_i) for the deck on the left. Based on the case study in Section 8.2, the weld between the cross beam and trough is again identified as the most critical detail in both types of OSDs. This is indicated by a warning symbol (!), suggesting that this detail may require additional attention. Furthermore, the case study showed that the combination of corrosion and fatigue leads to a significant increase in damage numbers. For such scenarios, it is essential to proceed with caution, and regularly monitoring is advised.

The 'Measure' column shows possible technical measures that can be taken. A green check mark (✓) indicates that the intended scenario meets the requirements, and no measure is necessary. A red cross (X) signals insufficient remaining life or performance. Then a measure should be taken and the rightmost column shows the effect of a particular measure for the reuse application. This overview serves as a first indication, providing guidance on which reuse options are viable in different scenarios.

10.3.4. Example routes Corrosion Fatigue

Based on the values obtained from the calculations in Step 2 of the guideline, several routes can be taken in Figure 10.8. To show how this works with numbers, the values from the case study in Section 8.3 are used.

In the case study, it is found for detail 2.2 that D_{CF} = 0.88 [-] for a specific predicted future scenario. This intended future scenario is now referred to as 'S_1'. To repeat again, it consists of the following characteristics:

- Additional lifetime = 50 [y], so total exposure time is 95 [y]
- Corrosivity class = C5
- Heavy vehicles allowed

Since D_{CF} < 1, this is OK. However, suppose an intended future scenario with a longer additional lifetime (S_2) is selected, for example:

- Additional lifetime = 75 [y], so total exposure time is 120 [y]
- Corrosivity class = C5
- Heavy vehicles allowed

Then there is a plausible chance that D_{CF} > 1. This is not acceptable, so a measure is needed. Depending on the requirements of the stakeholder, a certain measure may be appropriate or possible, while another may not. As shown in Figure 10.8, various measures are available, each with its own effect on the reuse application. Below, the overview is discussed using the outlined scenario (S_2) for some of the measures to show how it works.

Future function should stay the same

One option could be that the stakeholder wishes that the intended future function of the bridge remains the same, but the additional lifetime may be decreased. So, no concessions on the type of use, only on the duration. In that case, the pink route can be taken as shown in Figure 10.9 and explained below.

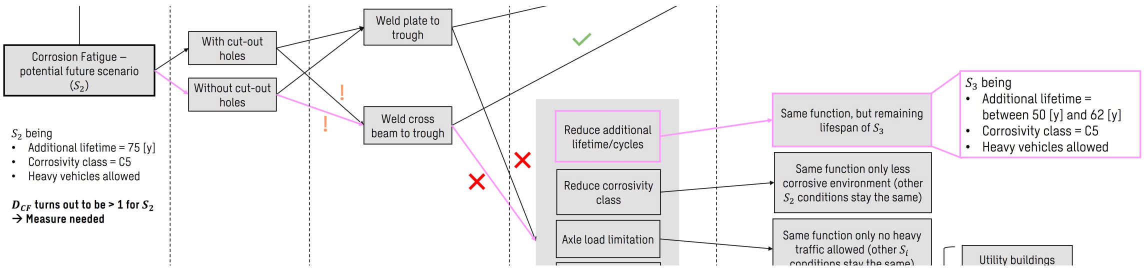


Figure 10.9: Zoom-in of overview to show pink route representing the measure of reducing additional lifetime for detail 2.2.

The path is followed for detail 2.2, so without cut-out holes and detail cross beam to trough. The measure of reducing the lifetime leads to a reduction in both the exposure time (influencing corrosion damage) and the number of load cycles of the heavy load (influencing the fatigue damage), and will thus contribute in two ways to lowering the damage number for Corrosion Fatigue damage. To exactly determine after how many years the D_{CF} is below 1, recalculations need to be done. Currently it is expected that it will be somewhere between S_1 and S_2, but it is unknown what the specific amount of years is. This can be calculated by determining the following two things:

1. For corrosion: A recalculation of the thickness reduction for the expected total amount of years should be done, so that the corresponding stress range in FEM can be read.
2. For fatigue: Rereading the allowed amount of cycles in the S-N curve for the newly found stress range, so that the damage number can be calculated.

So for the given detail, if the traffic intensity per year stays the same, the total amount of allowed cycles from the S-N curve of 1.0×10^7 [cycles] is reached after 107 [y]. This implies that there are 62 [y] of remaining fatigue life from today. However, this estimate is based on a stress range derived from a thickness reduction scenario (Scenario 8), which itself corresponds to only 50 [y] of remaining lifetime. Therefore, to determine the exact number of remaining years, the thickness reduction would need to be recalculated for the correct duration, and the stresses would need to be re-evaluated in the FEM model.

Nevertheless, based on the current findings, it can be concluded that the remaining fatigue life of this detail lies between 50 and 62 [y]. This conclusion can already be taken into account when assessing whether reducing the required additional lifetime is a favourable or effective measure.

Long future service life
It may also be the case that the stakeholder specifically wishes to keep a structure in service for a long period. In that case, no gain can be achieved by reducing the additional service life, but another technical measure could be selected, such as axle load limitation. This is represented by the blue route in Figure 10.10 and explained below.

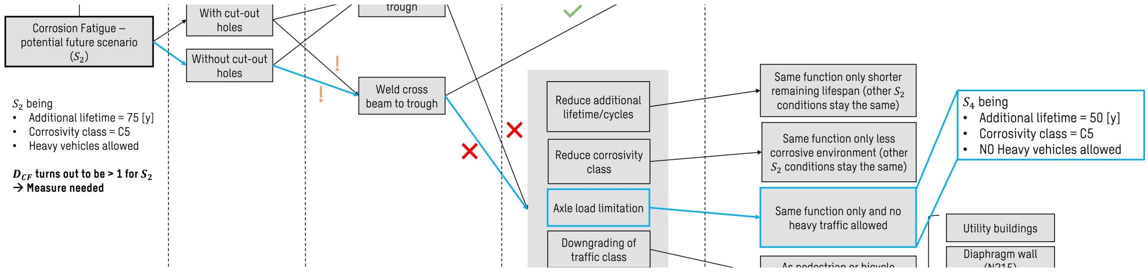


Figure 10.10: Zoom-in of overview to show blue route representing the measure of axle load limitation for detail 2.2.

Starting again with S_2 the route can be followed for detail 2.2. By applying the measure axle load limitation, the lifetime and environment may stay the same, but heavy vehicles will be no longer allowed (S_4).

So S_4 means:

- Additional lifetime = 50 [y], so total exposure time is 95 [y]
- Corrosivity class = C5
- Heavy vehicles NOT allowed

A new run of the FE model is required to determine the reduction in stress range and, consequently, the resulting decrease in damage number. It is possible that, for certain details, the stress range may even fall below the endurance limit, meaning the detail would theoretically have an infinite fatigue life.

10.4. Applicability of design guideline

First, the design guideline's deliverables and applicability are explained. Next, the possibilities for applying the guideline beyond the given case are discussed by including its current limitations and how these can be addressed.

10.4.1. What it offers

The design guideline provides an assessment procedure for the reuse potential of OSDs. These are interesting components due to their high strength-to-weight ratio and structural efficiency. It includes two types of OSDs, namely those with discontinuous troughs and those with continuous troughs. Including both types in the design guideline increases its applicability. Most Dutch bridges built after World War II contain OSDs with discontinuous troughs. Newer bridges are increasingly constructed with continuous troughs, as cutting the cross beams has become easier with modern laser techniques. By including both types, the guideline is relevant for both the current bridge stock and future designs.

The guideline focuses on three dominant damage mechanisms, namely corrosion, fatigue, and Corrosion Fatigue, which are considered the most critical according to literature. Users can assess the reuse potential for each of these mechanisms, which makes the guideline more comprehensive and increases its practical value.

Furthermore, applications range from reusing the full OSD to splitting it into sub-components. The guideline therefore does not limit itself to only one reuse type, but instead encourages exploration of various possibilities. This increases its value across a wider range of reuse scenarios.

Even further zooming out, an additional value of using the design guideline is that it results in the creation of a material passport for the specific component. This type of information is increasingly becoming part of standard asset management practices, especially regarding the transition toward a circular economy. Properly documenting the condition of a component not only supports reuse assessment but also helps to better understand its behaviour and performance. Such documentation ensures that critical information, such as loading history, damage patterns, and remaining capacity, is preserved over time. By standardizing the way reuse is assessed, making data traceable across projects, and embedding reuse thinking into regular engineering and asset management workflows, the guideline not only enables reuse in the short term, but also facilitates long-term knowledge transfer within the asset management cycle. This makes it a valuable tool not just for individual projects, but also for the broader transition towards a more circular construction sector.

10.4.2. Using it beyond the current case

Next, the possibilities for applying the guideline beyond the given case are discussed by including its current limitations and how these can be addressed.

Scaling up
Although the guideline was developed for OSDs of regional bridges, the underlying method is scalable. If the guideline were to be applied to larger, more provincial steel bridges, some additions would be needed. Not only does the span increase, but the number of heavy loads is also expected to be higher, requiring a more detailed fatigue assessment. As described in Section 8.2.6, FLM4 is recommended for bigger bridges, such as the Van Brienenoord bridge. FLM4 considers multiple types of heavy vehicles, which makes the assessment more accurate. Furthermore, EN 1993-1-9 lists up to 12 different detail types per OSD configuration. These should all be checked, not just the two governing ones included in the guideline. The two presented in the guideline give an initial indication but do not guarantee compliance for all details. So, for scaling up to larger bridges, the same three-step approach is needed, but Step 2 (fatigue analysis) must be extended.

Component expansion
The current analysis is focused on OSDs, while other bridge components such as vertical pylons or truss elements are left out of scope. However, it would be valuable to include these in future extensions of the guideline. This would increase its applicability and allow better use of the full residual capacity of a bridge. Components like trusses or pylons may be particularly interesting since they are often less exposed, or not exposed at all, to fatigue loading. This increases the chance of reuse and simplifies the reuse assessment. While these components are not included in the current scope, they could be added in a similar way. For example, an expansion of the guideline with specific rules and damage checks per component type would significantly increase the guideline's usability and efficiency.

Connections and joints
A factor that is currently outside the scope but could be integrated in future extensions is the treatment of connections. The feasibility of reuse often depends not only on the component itself, but also on how it is connected to the rest of the structure. Welded joints may limit disassembly or require local cutting, while bolted or demountable connections can simplify reuse. Moreover, new connections may need to be designed to fit the reused component into a new structural context. By including basic guidance on connection types and their implications for reuse, the guideline could better support practical implementation.

Functional and contextual expansion
The guideline is made for bridges, but steel reuse is also relevant in other construction sectors. To broaden the applicability of the guideline to other contexts, it is necessary to identify which aspects related to reuse are relevant in each context. For example, in buildings, fatigue does not play a role and reuse is mainly dependent on geometry and the amount of degradation. In temporary structures,

fast mounting and demounting may be more important than long-term strength. Still, also in these other contexts, the general method of archival research, modeling of damage to assess residual capacity, and then evaluating reuse potential, can be applied. By tailoring the input per sector, the procedure can be adjusted to different contexts.

Other materials
Although the method is developed for steel bridge components, the underlying process is more widely applicable. The systematic approach of archival research, modelling of damage to assess residual capacity, and then evaluating reuse potential, can also work beyond the current case. For other materials, the approach can also be used, if adaptations in Step 2 are made.

Sustainability as an overall goal
While the guideline focuses on reuse, it can be seen as part of a broader sustainability strategy. In many cases, reuse and recycling can be combined for the best overall result. For example, if a component is too damaged to reuse, it can still be recycled, while the other part is reused, provided the steel is properly separated. This mixed approach allows for the highest total value. By integrating a CO_2 impact into the guideline, the most sustainable option becomes visible. This would increase the value of the design guideline and make it more usefule beyond this specific case.

Conclusions

Three consecutive steps have been developed to determine the reuse potential of an OSD. The first step involves collecting the initial information. In step 2, the condition of the steel is assessed by determining the damage it has sustained over its service life. Based on this, step 3 identifies which reuse applications are viable and allows for selecting the most suitable high-value option for the specific situation. Lastly, the applicability of the design guideline is discussed by outlining its current value and exploring how its limitations can be addressed to enable broader use in other contexts.

Part III

From stakeholder perspectives to a broader systemic understanding

11

Interviews

This chapter introduces the various stakeholders involved and presents the interviews conducted with them. Based on the interview data, two pillars are identified, each appears to be associated with specific underlying obstacles. Furthermore, the proposed strategies in the interviews are elaborated.

11.1. Different stakeholders

In the civil construction industry, various companies and institutions operate, each having distinct roles and corresponding interests. To get an understanding of which party has which function and stakes, Table 11.1 has been compiled. Interviews were conducted with all the listed 'types' of stakeholders to obtain practical insights. The ultimate objective is to verify and expand upon the theoretical findings gained from the literature review, so that strategies can be developed that may stimulate the adoption of reuse across the entire supply chain.

Stakeholder	Role in the supply chain	Number of interviews
Client (project owner)	Defining project requirements, securing funding, and overseeing the project	3
Engineering consultancy firm	Providing civil engineering expertise regarding analysis and design in compliance with standards	4
Steel manufacturer	Manufactures and processes steel components based on design specifications and ensuring quality control	2
Contractor	Responsible for the execution of construction projects and ensuring structural integrity	4
Demolition contractor	Responsible for dismantling existing structures and recovering reusable components	1
Research institutions and firms	Conducting studies and finding innovative solutions	2

Table 11.1: Stakeholders and their roles in the construction industry.

11.2. Interview data regarding obstacles

In the interviews, stakeholders are asked about the obstacles they encounter regarding the reuse of steel. All the topics collected are listed below in Subsection 11.2.1, and an overview of this data with occurrences will be given in Subsection 11.2.2. The blue numbers between brackets (data [x]) are used later on in the analysis to refer back to specific citations in the interview data.

11.2.1. Description of obstacles from interviews

Availability of steel

The most frequently mentioned obstacle by all interviewees is the availability of steel. A key challenge is that choices are more limited when choosing for reused steel, as there can only be worked with the at that time available profiles. An example could be that 200 profiles are needed, but only 100 are available, or that a length of 12 meters is required, while only 11 meters can be found. — *Interviewee 3 (contractor)* Furthermore, the stock also needs to be at the right location and with the proper quality at the right time, so the availability of steel is a multi-layered issue data [9]. — *Interviewee 2 (client) and Interviewee 13 (contractor)*

Additionally, the available supply must be listed somewhere so that parties can know what is available. One example that was mentioned as potentially helpful is 'The Bruggenbank', but it is currently seen more as a promising concept than something truly useful, as its practical implementation is still limited. The information available on the 'Bruggenbank' is perceived as too superficial. Besides basic details about dimensions and material types, much more in-depth information is needed, such as maintenance reports and condition assessments. While the digital platform can potentially serve as a tool to easily offer bridge components, it does not immediately solve the practical logistical challenges of having the steel in the right place at the right time. — *Interviewee 1 (engineering consultancy firm) and Interviewee 7 (research firm)*

Steel storage locations

Whether a steel profile is considered 'available' for a contractor largely depends on where it is stored data [10]. Opinions differ a lot on whether there is enough storage space and enough suitable locations. Some interviewees say that finding a good storage place is a big challenge. It is also difficult to know how long the materials will need to be stored, because it is often unclear when or how they will be reused. If storage becomes too difficult to arrange, clients may quickly lose interest in reuse, since it takes extra time and effort data [6]. — *Interviewee 4 (engineering consultancy firm)*

Conversely, some interviewees argue that sufficient storage capacity already exists at manufacturers. Manufacturers are willing to use this space as a storage hub for reused steel and as this aligns with their business model, it would be an efficient solution for the market. — *Interviewee 8 (steel manufacturer) and Interviewee 10 (steel manufacturer)*

Under performance

Because there can only be chosen from a limited selection of available profiles, it may not be possible to select the most optimal profile, as would be the case with newly produced ones. This can lead to overdimensioning, which means that not all of the capacity of the reused profile is actually utilised and the profile is underperforming. So in certain cases, reuse might not be the best option, but melting down the steel and producing a perfectly fitting new profile could be more preferable. — Interviewee 3 (contractor) Moreover, this excess capacity needs to be considered in environmental assessments. In the described example of overdimensioning, more steel is needed to achieve a specific level of performance, which may contradict the environmental goals that is aimed for. — *Interviewee 14 (demolition contractor)*

Contractual limitations

Another significant issue that is mentioned related to material availability is the contractual limitations. "Currently, when materials become available in a 'traditional' project, they automatically go to the previous contractor", according to Interviewee 7. This process makes it very difficult to repurpose them, since they are locked into the contract. A notable example of this can be seen in the girders that were removed from the A9 highway in the Netherlands. These girders were owned by a Spanish contractor. Here, conflicting interests arise, because the Spanish contractor simply seeks to maximize profit and will not have an interest in promoting sustainability practices in the Netherlands. To still make the girders available, the challenge is how to ensure that these can still be 'harvested' rather than demolished data [12]. — *Interviewee 7 (research firm)*

Time taken in a project
It is noted that material exchange itself is not the main issue, but rather the problem lies in the project schedule. Platforms have been established to facilitate material exchange, such as 'The Bruggenbank'. However, such a platform will not work in practice if the offer from the platform is not considered in time by the client, as the scope and schedule of a project are already determined before the project starts. Experience shows that there are tight timelines, designs must be completed by a specific deadline, and contracts must be finalized quickly. Often, the question of incorporating reused materials only arises later. People are usually willing to do so, but by that point, it is too late, because sourcing suitable steel at short notice is almost impossible. This results in the ambitions being lost data [7]. — *Interviewee 4 (engineering consultancy firm)*

Major time between contracting and engineering
This issue of time is recognized by other interviewees. The gap between project initiation and project execution is often a period of about 3, 4, or even 5 years. A simple example is that a profile might be available at the start, but no longer be available when it is time for execution. — *Interviewee 8 (steel manufacturer)*

Lack of knowledge of clients
Another frequently mentioned obstacle is the difficulty of assessing the material properties and condition of steel for reuse. The key issue here is that the required historical data is unknown by clients and difficult to determine. — *Interviewee 3 (contractor)* This is further confirmed by other interviewees, who highlight poor monitoring by clients as a significant obstacle. There is often insufficient data on existing structures. As a result of lacking information, extensive destructive testing would be required, which would render the structure temporarily unusable and incur high costs. Closures and disruptions during the construction process are significant disadvantages to clients and as a result, enthusiasm for reuse will quickly fade away data [4]. — *Interviewee 5 (engineering consultancy firm) and Interviewee 7 (research firm)*

This lack of data is confirmed by the client itself and it is agreed upon the fact that this is also partly attributed to its own fault. The historical data in archives has not been well maintained, and a significant amount of time and effort is required to organize everything properly. Since this process is so time-consuming and demanding, it leads to a cautious attitude towards reuse among clients data [5].— *Interviewee 15 (client)*

Issuing guarantees/certificates
Additionally, the lack of historical information from clients makes it harder to automatically link certificates to the materials. So in order to be able to guarantee the quality of the steel, which is needed to obtain availability of steel with a proper quality, a specific stakeholder must be held responsible for this process data [11]. — *Interviewee 1 (engineering consultancy firm)* Manufacturers would be willing to take on this role, but there still exists a lack of clear specifications regarding mandatory testing standards. — *Interviewee 10 (steel manufacturer)*

Lack of design guidelines
A frequently mentioned obstacle is the lack of standardized design rules for reusing structural components from bridges. The lack of a standardized verification procedure results in doubts and a hesitant attitude towards reuse data [2]. Currently, only the NTA8713 design guideline exists for reusing components from utility buildings. Several interviewees mention that this standard has been well-received and successfully implemented in the industry. Adoption of the standard has eliminated doubts about the quality of reused steel from industrial buildings since every inspection now follows the same recognized procedure. This results in confidence and trust from clients. — *Interviewee 1 (engineering consultancy firm) and Interviewee 10 (steel manufacturer)*

Lack of scientific basis regarding reuse
One of the biggest obstacles to developing these design guidelines is that determining the remaining service life is still difficult and unclear for steel bridge components. The behavior of fatigue-loaded steel is still not perfectly understood. So for now, only the easier options (non-fatigue loaded profiles) are

chosen for reuse, which require less proof and can be reused right away. As a result, the available supply becomes more limited data [15]. — *Interviewee 3 (contractor)*

Laws and regulations are dynamic
It is also mentioned that standards and regulations are dynamic data [39].One example given is bridges built before 2011, which were designed according to the old standards and now often no longer meet the current requirements. Usually, standards become stricter over time, and this makes reuse possibilities even smaller. — *Interviewee 5 (engineering consultancy firm) en Interviewee 14 (demolition contractor)*

Negative attitudes
The perception of conservatism and a traditional mindset of particular individuals is confirmed by almost all interviewees data [1]. Rijkswaterstaat is seen as cautious and finds aspects of reuse daunting. Other traditional clients simply want to take the easiest route and buy steel as quickly as possible. — *Interviewee 4 (engineering consultancy firm) and Interviewee 15 (client)* However, the interviewees also point out that the supply chain is gradually developing, since clients are starting to ask better questions regarding reuse. — *Interviewee 4 (engineering consultancy firm) and Interviewee 11 (engineering consultancy firm)*

Some interviewees have a negative attitude because reuse is not always the best option, according to them. An existing bridge will always perform worse in terms of maintenance compared to a new one, which makes reuse less preferable data [35]. Furthermore, the steel is second-hand and has already been used. There is already some damage, and it probably can not last another full lifespan of around 75 years. So, a reused steel profile typically offers a shorter remaining service life compared to a new one data [37]. — *Interviewee 2 (client) and Interviewee 5 (engineering consultancy firm)*

In addition, a hesitant attitude is present because the reuse of bridge components may be less impactful compared to the reuse of, for example, overpasses data [40]. Overpass components have standard dimensions and can be made easy to disassemble. Currently, standardisation products are being developed for overpass components with a lifespan of 150 to 200 years. This makes it possible to reuse certain parts multiple times and use materials more efficiently. For bridges, this is more difficult because there are fewer standard dimensions, so the process of standardisation does not apply. — *Interviewee 15 (client)*

Conversely, some interviewees from the market have a more forward-thinking perspective. They believe that the supply chain is lagging behind and most of the obstacles are already solved. One example of this is the issue of lacking design standards. Until recently, there were no standards regarding reuse for utility buildings either, as construction was either classified as 'new construction' or 'existing structures', with reuse falling somewhere in between. While some view this as an obstacle, others see it as an opportunity. It can be an opportunity, provided that authorities are engaged early in the process. By discussing requirements and what needs to be demonstrated for approval in advance, authorities can be convinced and give approval, even in the absence of standards. Therefore, claiming that the lack of standards is an obstacle is debatable. It depends on the willingness of the contributing stakeholders. — *Interviewee 7 (research firm)*

Lastly, architects often prefer to see something new and may therefore be opposed to the reuse of steel data [36]. Structural engineers are generally seen as traditional and risk-averse data [32]. When new innovations are proposed, such as, for example, designing demountable steel components, this also means that new weak connections are formed. Structural engineers tend to focus purely on the posed risks, rather than seeing the benefits of demountable connections. — *Interviewee 1 (engineering consultancy firm) and Interviewee 15 (client)*

Differences in attitudes between clients
It was noted that the level of enthusiasm varies among clients and that they should not all be treated as a single group. This mainly relates to the risks involved in the projects, or in other words, the consequence classes. Generally speaking, the higher the consequence class of the structure and therefore the associated risks, the less eager the client is willing to participate. — *Interviewee 10 (steel manufacturer)*.

Client does not ask for it
Almost all interviewees indicate that one of the biggest problems is that the client does not ask for

reuse in their tenders. The market itself will not be willing to take the risks that are associated, as they are too costly. For this reason, the client must bear the risks and accept that reuse practices might be more expensive at the beginning. — *Interviewee 1 (engineering consultancy firm), Interviewee 4 (engineering consultancy firm), and Interviewee 12 (contractor)*

This is confirmed by a client, who describes an example where an old factory hall was turned into a new pedestrian bridge. This project was so successful in terms of reuse practices, because circularity was already central in the tender. — *Interviewee 2 (client)*

A statement made by a contractor in one of the interviews is: "If you always ask for what you have always asked for, you will always get what you have always gotten" data [13], according to Interviewee 16. This again refers to the idea that the client specifically needs to demand reuse (ask), in order to create a supply (get).

Another interviewee points out that the current uncertainties and therefore risks regarding reuse should not be placed on the market. An example is given of the 'Bouwfraude' in the Netherlands in the 2000s, where contractors took on risks they could not bear just to remain competitive. Eventually, this escalated and ended badly. Therefore, this person suggests that the only party that can take on these risks is the client. — *Interviewee 3 (contractor)*

A client also agrees that clients must take responsibility for these risks. Innovations, such as reuse, inherently involve many uncertainties and risks. It is therefore good for the client to take the lead, implement it, and learn from the process along the way. As the process progresses, the risks will become increasingly manageable, and as they shrink to the point where a business case emerges for the market, the market will take over. — *Interviewee 15 (client)*

Nonetheless, this client also points out that therefore not all the blame can be placed on clients. Sustainability involves developing new things and innovations, which requires investment. The market is eager to participate and has its own ambitions, but they still look to the client to take the first step, provide financing, and bear the risks of trying it out data [14]. — *Interviewee 15 (client)*

Confusion about the goal
Almost all interviewees mention that it is unclear what the supply chain should strive for. Sustainability objectives come in various forms, such as minimizing CO2 emissions, minimizing environmental impact (MKI), and also maximizing designing for disassembly. There exists a feeling of confusion that leads to negative attitudes and ambitions being lost data [3]. To achieve more reuse, it must be clearer for stakeholders what the goal is within a project. — *Interviewee 4 (engineering consultancy firm) and Interviewee 16 (contractor)*

Another interviewee confirms the aforementioned and provides an example by comparing it with the two neighboring countries, Germany and Belgium. The government of the Netherlands always tells a nice story, but after this it remains still unclear what needs to be done. In contrast, Germany has has taken concrete steps by gathering a lot of knowledge about all materials and also mapped their conditions. On the other hand, in Belgium, the problem is avoided by simply putting up a traffic sign that shows a load limitation to avoid having to look at it anymore. So, in the Netherlands, policy-wise clearer action points need to emerge so real steps can be taken. — *Interviewee 3 (contractor)*

Removal of coating
Another less frequently mentioned obstacle, but one that three interviewees consider the biggest challenge, is coating. The main issue is that environmentally harmful substances and heavy metals such as chromium-6 are used in coatings. Removing these types of coatings is extremely expensive. These higher costs destroy the entire business model of reuse. If this major issue can not be resolved, reuse will remain a small-scale, goodwill effort by a few dedicated clients. As a result, large-scale availability will be impossible, and reuse is unlikely to become common practice data [16]. — *Interviewee 7 (research firm), Interviewee 9 (research firm), and Interviewee 14 (demolition contractor)*

Costs uncertainty
Because reuse is still a new concept and in its early stages, not all processes and associated costs are clearly understood yet. For example, the additional demolition processes and storage costs are not perfectly known. Therefore, some smaller companies will be hesitant and unable to contribute in reuse because they lack the financial leeway data [8]. They will wait for the larger parties to figure out which

processes are involved and how much of an environmental (ENVI) or MKI reduction can be achieved through reuse. — *Interviewee 12 (contractor)*

The value of remeltable steel is high
Another cost-related obstacle is the relatively high value of scrap steel, which makes reuse economically unattractive for many companies. As a result, most companies tend to choose the most beneficial option and therefore sell the steel as scrap, instead of investing time and money into how it can be reused. — *Interviewee 8 (steel manufacturer)*

11.2.2. Overview of obstacles from interviews

The collected obstacles from the interviews are structured in Table 11.2. Based on this, the frequency of each type of obstacle is counted, as shown in Table 11.3. The counting will be used in the analysis of this interview data, which is done in Section 11.3.

	Obstacle	Client	Engineering consultancy firm	Steel manufacturer	Contractor	Demolition contractor	Research institutions and firms
Policy and regulatory	1. Lack of EU regulations	15	(4)	(8)	16	(14)	
	2. Contractual limitations	2					7
	3. Laws and regulations are dynamic		5			14	
Cultural and social	4. Negative attitudes	6 – 15	1 – 4 – 5 – 11	**10**	3 – 13 – 16	14	7 – 9
	5. Client does not ask for it	2 – 15	1 – 4 – 5		12 – 16		9
	6. Differences in attitudes between clients			10	16		
	7. Confusion about the goal	15	4		3 – 16		
	8. Major time gap between contracting and engineering	2	1 – 4	8			9
	9. Issuing guarantees/ certificates	2 – 15	1	8 – 10		14	7 – 9
	10. Time taken in a project		4			14	
Technical	11. Availability of steel	2 – 6 – 15	1 – 4 – 5 – 11	8 – 10	3 – 12 – 13 – 16	14	**7 – 9**
	12. Steel storage locations	2	4				7
	13. Lack of design rules	(2) – 15	1 – 5	10	3	(14)	7 – 9
	14. Under performance		5	8	3	14	
	15. Removal of coating	15				14	7 – 9
Economic	16. Costs uncertainty	(2) – 15	1 – (5)	8	3 – 12		7 – (9)
	17. The value of remeltable steel is high			8 – 10			
Knowledge and skill	18. Lack of knowledge of clients	2 – 15	5	10	3 – 12 – 16		7
	19. Lack of scientific basis regarding reuse	15			3 – 12		9

Table 11.2: Overview of all obstacles mentioned in interviews by different stakeholders.

Obstacle	Occurrence	Obstacle	Occurrence
1. Lack of EU regulations	5	11. Availability of steel	16
2. Contractual limitations	2	12. Steel storage locations	3
3. Laws and regulations are dynamic	2	13. Lack of design rules	9
4. Negative attitudes	13	14. Under performance	4
5. Client does not ask for it	8	15. Removal of coating	4
6. Differences in attitudes between clients	2	16. Costs uncertainty	9
7. Confusion about the goal	4	17. The value of remeltable steel is high	2
8. Major time gap between contracting and engineering	5	18. Lack of knowledge of clients	8
9. Issuing guarantees/ certificates	8	19. Lack of scientific basis regarding reuse	4
10. Time taken in a project	2		

Table 11.3: Obstacles and their occurrence with a green (low) to red (high) color gradient.

11.3. Analysis of interview data regarding obstacles

The obstacles mentioned in the interviews, described in Section 11.2, have been analyzed. The insights are explained below.

Firstly, the interview data reveal a total of 19 distinct obstacles. The responses indicate both a wide variety in the types of obstacles mentioned and a notable variation in how frequently each obstacle is raised. As shown in Table 11.3, two obstacles were mentioned substantially more often than the others, namely 'Negative attitudes' (mentioned by 13 out of 16 interviewees) and 'Availability of steel' (mentioned by all interviewees).

These two obstacles are consistently encountered across the interviews and are therefore conceptually grouped under the term 'pillars' in the scope of this study to facilitate interpretation. The data further suggests that these two pillars are related to several other obstacles mentioned during the interviews. These obstacles from the interviews are now labeled in this study as 'underlying obstacles' to facilitate the analysis as well. The considered relationships between pillars and underlying obstacles are supported below per pillar. References to the interview data can be found by clicking on 'data [x]', with x indicating the citation number.

11.3.1. Underlying obstacles associated with 'Negative attitudes'

'Negative attitudes' is the first identified pillar in this study. The construction industry is seen as a conservative chain, according to the interview data: "The perception of conservatism and a traditional mindset of particular individuals is confirmed by almost all interviewees" data [1]. In addition to this intrinsic characteristic of the industry, this negative attitude appears to be related to several other underlying obstacles:

- Firstly, interviewees point to the lack of design guidelines for reusing structural components in bridges. One interviewee explains: "The lack of a standardized verification procedure results in doubts and a hesitant attitude towards reuse" data [2]. In the context of utility buildings, the introduction of such a standard a few years ago is reported by interviewees to have increased confidence among actors.
- In addition, multiple forms of sustainability exist, such as minimizing CO_2 emissions or maximizing reuse. Several interviewees indicate that these goals are sometimes seen as conflicting. The absence of a clear prioritisation is reported to create, as one interviewee describes it, "a feeling of confusion that leads to negative attitudes and ambitions being lost" data [3].
- Interviewees also describe challenges related to the availability and organisation of historical data. To assess whether components are fit for reuse, their condition must be known, which often involves destructive testing. This is described by interviewees as costly and potentially disruptive. One interviewee notes: "Closures and disruptions during the construction process are significant disadvantages to clients and as a result, enthusiasm for reuse will quickly fade away" data [4]. While efforts are being made to improve data organisation, another interviewee states: "since this process is so time-consuming and demanding, it leads to a cautious attitude towards reuse" data [5].
- Furthermore, the need for appropriate storage locations is mentioned by interviewees. Several note that finding suitable storage space can be challenging. As one explains: "If storage becomes too difficult to arrange, clients may quickly lose interest in reuse, since it takes extra time and effort" data [6].
- The timing of reuse considerations within projects is also mentioned as a contributing factor. Interviewees explain that projects often follow tight schedules, which may not align with the later introduction of reuse ideas. One interviewee notes: "Often, the question of incorporating reused materials only arises later. People are usually willing to do so, but by that point, it is too late, because sourcing suitable steel at short notice is almost impossible. This results in the ambitions being lost" data [7].
- Finally, some interviewees highlight cost uncertainty as a barrier for smaller actors. One interviewee states: "Some smaller companies will be hesitant and unable to contribute to reuse because they lack the financial leeway" data [8]. Because reuse is relatively new, cost estimations are not

yet well established, which may require a certain degree of financial flexibility. Smaller companies may prefer to wait for larger actors to take the lead.

11.3.2. Underlying obstacles associated with 'Availability of steel'

'Availability of steel' is the second identified pillar in this study. This issue arises because choices are more limited when opting for reused steel. Furthermore, this obstacle is also described as having multiple dimensions. As stated by one interviewee: "the stock also needs to be at the right location and with the proper quality at the right time, so the availability of steel is a multi-layered issue" data [9].

Several underlying obstacles, based on Subsection 11.2.1, are perceived by interviewees to contribute to the issue of availability:

- Firstly, reused steel needs to be physically present near the location where it is intended to be applied. As one interviewee notes: "whether a steel profile is considered 'available' for a contractor largely depends on where it is stored" data [10]. Limited space or a small number of locations is described as a factor that can reduce available stock.
- In addition, the material properties and conditions must be known to apply reused steel safely. When this information is lacking, the reuse potential can not be assessed, and the component is not considered part of the 'available' stock. Interviewees mention that currently no stakeholder in the supply chain is responsible for issuing certificates that document these properties. One interviewee states: "a specific stakeholder must be held responsible for this process" data [11].
- Another issue mentioned by interviewees is that reused steel is often tied to a specific contract with the original contractor, which complicates its repurposing. As one interviewee puts it: "To still make the girders available, the challenge therefore is how to ensure that these can still be 'harvested' rather than demolished" data [12].
- A frequently mentioned obstacle is that clients often do not request reuse in their tenders. Interviewees suggest that as a result, the market perceives limited incentive to build up a stock of reusable components. One interviewee states: "If you always ask for what you have always asked for, you will always get what you have always gotten" data [13]. However, another interviewee points out: "The market is eager to participate and has its own ambitions, but they still look to the client to take the first step" data [14]. This reflects a shared uncertainty between clients and the market regarding leadership in reuse efforts.
- Some interviewees highlight the lack of a scientific basis, especially concerning the remaining service life of fatigue-loaded steel. One interviewee explains: "So for now, only the easier options, non-fatigue loaded profiles, are chosen for reuse, which require less proof and can be reused right away. As a result, the available supply becomes more limited" data [15].
- Lastly, environmentally harmful coatings are mentioned by interviewees as a limiting factor. If no cost-effective removal solution is found, one interviewee states: "large-scale availability will be impossible, and reuse is unlikely to become common practice" data [16].

Conclusions
Based on Subsection 11.3.1 and 11.3.2, it can be concluded which of the underlying obstacles appear to be associated with the two identified pillars. This is depicted in Figure 11.1.

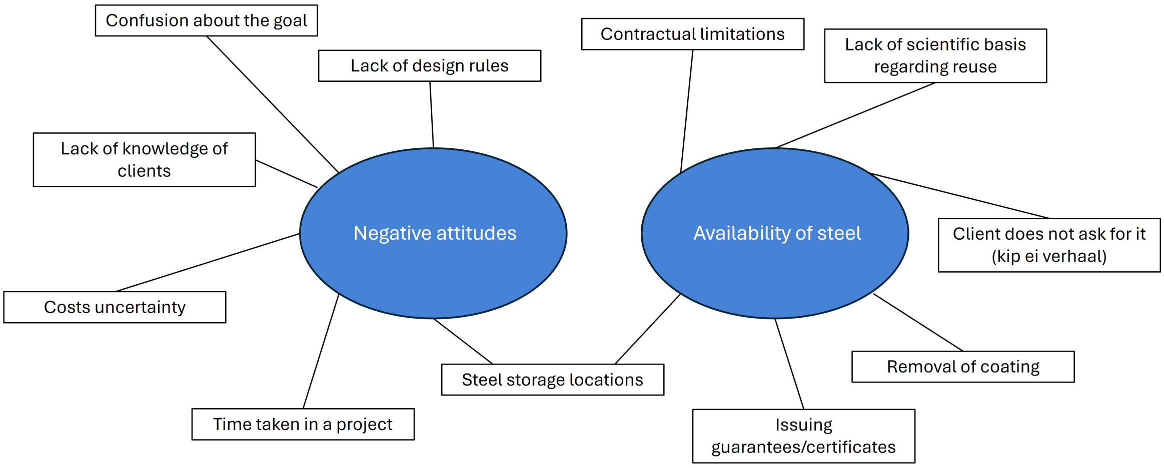


Figure 11.1: Developed overview of underlying obstacles (rectangular shaped) that appear to be associated with the two identified pillars (oval shaped).

Remarks
The two pillars were chosen based on which obstacle was mentioned most frequently. Since both topics 'Negative attitudes' (Hart et al., 2019) and 'Availability of steel' (Kanyilmaz et al., 2023) were identified earlier in the literature review, the researcher specifically asked interviewees to agree or disagree with these obstacles. This may have distorted the counting, because this specific question was not asked for the obstacles that were not identified through the literature research. However, an interviewee is only counted if they agree with the obstacle, which is why the decision is still made to choose the pillars based on which ones are mentioned most often.

Additionally, a contradiction can be recognized, as all interviewees mention that they are open to reuse and ambitious to contribute, but a negative attitude is also pointed out across all parties in the market. This may be due to the choice of interviewees. There could be a selection bias, as described in Chapter 2. In other words, people who are interested in reuse are more likely to agree to participate in the interview, which could explain this discrepancy.

11.4. Comparison between literature and interview data

Furthermore, a comparison is made between the interview data and the literature review.

Table 11.4 presents a smaller part of Table 11.2, and shows which stakeholders agree with the identified obstacles from the literature study.

- If an interviewee number is listed in the row of the particular obstacle, it means that the interviewee agrees on this obstacle and brought it up themselves during the conversation.
- If the number appears in parentheses, it indicates that the interviewee agrees with it, but did not mention it on their own, so only confirming it after being asked by the researcher.

Obstacle from literature	Mentioned by		
	Client	Engineering consultancy firm	Steel manufacturer
Availability of steel	2 – 6 – 15	1 – 4 – 5 – 11	8 – 10
Lack of design rules	(2) – 15	1 – 5	10
Lack of EU regulations	15	(4)	(8)
Costs uncertainty	(2) – 15	1 – (5)	8
Negative attitudes	6 – 15	1 – 4 – 5 – 11	10

Obstacle from literature	Mentioned by		
	Contractor	Demolition contractor	Research institutions and firms
Availability of steel	3 – 12 – 13 – 16	14	7 – 9
Lack of design rules	3	(14)	7 – 9
Lack of EU regulations	16	(14)	
Costs uncertainty	(3) – 12		7 – (9)
Negative attitudes	3 – 13 – 16	14	7 – 9

Table 11.4: Overlap between obstacles in the literature and those mentioned by stakeholders in the interviews.

Next, Table 11.5 is compiled to show how many people in total mentioned and/or agreed upon each obstacle, or so-called its ‘occurrence’.

Obstacle	Mentioned themselves	Confirmation after being asked	Total occurrence
Availability of steel	16		16
Lack of design rules	7	2	9
Lack of EU regulations	2	3	5
Costs uncertainty	4	3	7
Negative attitudes	13		13

Table 11.5: Occurrences of overlapping obstacles between the literature and interviews, visualised using a red (low) to green (high) colour gradient.

Explanation

Based on Table 11.5 it is observed that there are similarities between the obstacles found in the literature and the interview data. The most frequently mentioned obstacle in the interviews, which is also present in the literature, is ‘Availability of steel’. In the literature, this obstacle is referred to as the ‘sourcing of the steel’ (Kanyilmaz et al., 2023), and described in Section 4.1. This obstacle is confirmed and self-mentioned by all interviewees (16 out of 16). Additionally, the obstacle ‘Negative attitudes’ is also identified in the literature, namely in Section 4.5 as lack of ‘engagement of the construction ecosystem’ (Hart et al., 2019). This obstacle is also mentioned by 13 out of 16 stakeholders during the conversations. These two points show alignment between theory and practice.

There is some variation between the literature and the interview data regarding two of the identified obstacles. The obstacle ‘Costs uncertainty’, which is identified in the literature in Section 4.4, as uncertainty in ‘costs’ (Dunant et al., 2018), is supported in approximately half of the interviews. Similarly, the obstacle ‘Lack of design rules’, which is in the literature found in Section 4.2, as ‘re-certification of design standards’ (Kanyilmaz et al., 2023), is also only partially confirmed by the interviewees. Both obstacles were mentioned a few times spontaneously by interviewees, a few times confirmed by the researcher’s question, and also approximately half of the times not agreed upon. Therefore, there is no alignment between theory and practice on these points.

The last identified obstacle, ‘Lack of EU regulations’, is described in Section 4.3 as lack of ‘legal frameworks’ (Condotta and Zatta, 2021; Halonen et al., 2024). This obstacle is self-mentioned by only 2 interviewees. After probing by the researcher, this obstacle is only confirmed by 3 other persons, so denied by 11 interviewees. This indicates a difference between theory and practice.

Furthermore, apart from these 5 obstacles, 14 other obstacles were identified in the interviews. These 14 were not found in the literature review, which makes this a notable difference.

Conclusions

The various observations may provide new insights within this field of research.

- For both ‘Availability of steel’ and ‘Negative attitudes’, it appears that these obstacles are recognized in both theory and practice. These two were previously identified in Section 11.3 as the pillars in this study, and are therefore considered relevant when exploring possible strategies to stimulate adoption among stakeholders.

- For the obstacles 'Lack of design rules' and 'Costs uncertainty', there seems to be partial agreement between theory and practice. This may suggest that these obstacles are partly acknowledged in the literature, but interpreted differently or more broadly in practice. A lack of familiarity among interviewees may also play a role.
- In the case of 'Lack of EU regulations', there appears to be a disalignment between theory and practice. This may indicate limited awareness among interviewees, or that they consider the topic potentially relevant at a later stage.
- 14 other obstacles were mentioned in practice that did not emerge from the literature review. This may point to a gap between theory and practice.

Following these findings, the next section presents potential strategies mentioned during the interviews in relation to the identified obstacles.

11.5. Interview data regarding strategies

The underlying obstacles associated with each of the two pillars may influence the adoption of reuse in the supply chain. To explore possible responses to these obstacles, the interviews included an open question asking which strategies could be considered. The interview data regarding strategies is presented below and is then analyzed. As before, the blue numbers in brackets (data [x]) refer to specific citations from the interview data and are used in the analysis.

11.5.1. Description of strategies from interviews

Make reuse a mandatory requirement in tenders

For many interviewees reuse is currently seen as something optional. There exists ambition, but it is not always deeply embedded in the way construction is carried out. Other factors such as 'time', 'disruptions', and 'costs' are contractually mentioned and take priority. Therefore, a lot of interviewees mention that the political approach needs to be reorganized so that, when it comes down to it, reuse is prioritized data [23]. This can be achieved by including it in legislation, either directly or indirectly. It is possible to give the supply chain specific requirements for the percentage of reused materials through procurement rules or contractual obligations. — *Interviewee 15 (client)* Another way is introducing legislation regarding CO2 taxation. If companies will have to pay per amount of CO2 emission, reused steel will gain an economic advantage, and the business case will take off. — *Interviewee 14 (demolition contractor)*

A first step in changing legislation was taken with the release of the 'Dwingende MKI' report, which serves as an advice to the Ministry of Infrastructure and Water Management to make environmental impact a mandatory criterion in tenders for all infrastructure works. Currently, only 50% of tenders include a sustainability criterion, meaning the other half still lacks this requirement. By legislating the requirement for clients to ask for environmental impact assessments, contractors will see it as an opportunity to profit from it. If they can make a profit, they will be willing to invest data [29]. — *Interviewee 16 (contractor)*

In addition to this development, there is another report that helps guide the supply chain in the right direction. This report is called 'Het nieuwe normaal' and will contribute to having a clear language to gain more national consensus on how sustainability is pursued data [17]. From Section 11.2, it was clear that there is a lack of focused direction, which caused confusion in the market. By developing this clear language, all clients will need to request in the same way, and this can prevent contractors from hearing different requests. — *Interviewee 4 (engineering consultancy firm) and Interviewee 15 (client)*

Reward the front runners and push the peloton

It is mentioned by a few interviewees that a reward system would stimulate them to try and invest more in reuse practices data [26]. This way of rewarding can be achieved through a so-called 'front runner - peloton approach'. The 'peloton' here represents the general level of what the market is capable of. Within the market, there are some who are more forward-thinking and lead the way, and these are known as the 'front runners'. The leaders will come up with innovations, and they should be rewarded because they are often paying more to come to these higher levels. On the other hand, the peloton is seen as slower and has a lower level, and it needs to be pushed forward through demands and regulations. By rewarding the front runners through government interventions and pushing the peloton to a higher level by introducing laws and regulations the entire chain will eventually be set in motion data [27]. — *Interviewee 15 (client) and Interviewee 16 (contractor)*

Rewarding can be done by allocating more funding to clients and other market leaders. Innovations and trial projects are costly, and front runners in the field will always pay more. There is a lot of lobbying in politics to secure additional funds, but this is still not enough. Receiving extra funds will provide more room to demand sustainability, thus helping to stimulate the market. — *Interviewee 15 (client)*

However, it is also noted that governmental funds will never be enough to cover all costs data [38]. Clients should not hide behind these higher costs. The market must make extra efforts to find innovative solutions, and clients must do the same.Both sides need to compromise for success. — *Interviewee 16 (contractor)*

Develop contract requirements for circular demolition
In addition to the policy aspect, a strategy is also needed to address the most frequently mentioned obstacle in Section 11.2, namely to match demand and supply. These two aspects have different backgrounds, but they are closely related. Since legislation and policy are making it mandatory for clients to ask for reuse, the result will be a high demand for circular materials and therefore circular demolition. Several interviewees indicate that if demolition is done in a circular way, a supply of reused steel will be obtained, and when there is supply, demand again automatically follows. —*Interviewee 7 (research firm) and Interviewee 16 (contractor)*

So a first step in obtaining supply, is developing contract requirements for circular demolition data [24]. The first steps are already taken by certain consortia such as 'Betonakkoord' and 'Bouwakkoord Staal', which have prepared a document called 'Circulair slopen.' This document is an addition to a previously issued report called 'Circulair Materialen Plan' from the ministry. The addition was made because the 'Circulair Materialen Plan' report was not ambitious enough and did not even meet the minimum requirements of the market. As a result, the consortia created an improved version. With this 'Circulair slopen' note, the first step in developing requirements for circular demolition and therefore getting the market moving regarding supply and demand is established. — *Interviewee 16 (contractor)*

Create storage locations for obtained supply
Some interviewees focus less on the demolition process and more on how the storage of reused steel will be managed. Several suggest that clients should take on the role of owning 'support locations' or hubs, where materials can be stored data [19]. For contractors, these locations are often too expensive, which makes the business case for reuse less appealing. One interviewee pointed out that it would be interesting to see whether clients could own a site where contractors could visit and purchase components at a regular fixed price, without the added cost of storage. This approach would make the business case for reuse more attractive. — *Interviewee 7 (research firm)*

On the contrary, other parties suggest that steel manufacturers could perfectly take on this role as they already possess large storage locations data [31]. Steel manufacturers also express their willingness to assume a management function in this regard. For sheet piles, the use of so-called 'verkoop-terugkoop' contracts is already more common, where the contractor only pays for the use of the materials and not for ownership. This could be extended to other types of steel profiles. The 'verkoop-terugkoop' contracts also provide better insight into what will be circulating in the market in the future, which is an additional benefit. — *Interviewee 8 (steel manufacturer)*

This idea is supported by several other interviewees. The advantage of a manufacturer serving as a hub, compared to a contractor, is that they can serve a larger number of projects. For example, if a particular steel component does not fit in project A, it might fit in project B. Since a manufacturer works on multiple projects simultaneously, there are many more types of components in circulation. The turnover rate of materials is much higher with a manufacturer than with a contractor. — *Interviewee 9 (research firm), Interviewee 10 (steel manufacturer), and Interviewee 13 (contractor)*

A contractor also agrees with this and expects that these hubs will not be located at the contractor's site, but rather at external inventories from parties that can supply multiple contractors. A contractor does not have the money or space to store materials, and storage is a different business model from what they do. A higher turnover rate is also beneficial for them. — *Interviewee 12 (contractor)*

An additional benefit of having a larger supply is that the reuse process becomes less situation-specific and can be applied more broadly data [29]. This reduces the time component and lessens the strong dependency on the schedule of a particular project, making it more attractive for the contractor. — *Interviewee 9 (research firm)*

Providing certificates and guarantees
Another benefit of the manufacturer becoming the stockholding party is that they can provide quality assurance. Currently, the lack of historical information from clients makes it hard to automatically link certificates to the materials. So in order to guarantee the quality of the steel, it must be tested. Manufacturers would be willing to take on this role, if clear specifications regarding mandatory testing standards are developed data [30]. — *Interviewee 10 (steel manufacturer) and Interviewee 14 (demolition contractor)*.

Train the chain through partnerships
It has been noted that there is a lack of knowledge among the supply chain. Clients often rely on the expertise of consulting firms. — *Interviewee 5 (engineering consultancy firm)* However, it is also mentioned that engineers from consultancy firms need to be trained as well. A proposed strategy for this is creating partnerships through which regular discussions can be held. One such collaboration is the ‘Coalitie circulaire bruggen’, a group of clients who share experiences to build trust and overcome challenges. There are also coalitions that bring together front runners from various backgrounds, such as contractors, demolition companies, and clients. They are all willing to experiment together in order to ultimately innovate. Therefore, sharing knowledge and open communication are essential for training the supply chain data [25]. The knowledge gained within these partnerships can later be shared with the wider market. — *Interviewee 15 (client) and Interviewee 16 (contractor)*

Additionally, training clients can help reduce the differences in attitudes between them. By explaining the benefits and sharing successes, more enthusiasm and trust can be generated. — *Interviewee 10 (steel manufacturer)*

It is also often mentioned that raising overall awareness throughout the chain is essential for developing a long-term strategy. This is because significant long term benefits can be achieved, if action is taken now to change the design approach. For example, when designing a new structure, the end of its lifespan should already be considered, allowing certain components to be designed for reuse. An example of this is including a slight over-dimensioning of a profile that creates ‘cutting’ space, ensuring that reuse remains possible. — *Interviewee 8 (steel manufacturer)*. Obtaining this kind of knowledge now, will contribute to significant results in the long term. However, it is noted that the client may not be willing to make these long-term choices because the costs will be higher in the short term, since over-dimensioning generally costs more. Therefore, sufficient incentives will be needed. — *Interviewee 15 (client)*

Furthermore, training the chain can be done through the adoption of new forms of contracts. There are recent developments in the chain with new forms of contracts, such as ‘Twee-fasen-contracten’ or ‘Bouwteams’, where designing is done more collaboratively with the client. This allows both contractors and clients to experiment more because the risks are shared. This has an encouraging effect on reuse. — *Interviewee 12 (contractor)*

Another advantage of forming these types of forms of contracts is that it is necessary to establish more partnerships. The benefit of partnerships is the exchange of knowledge, which means that not everything needs to be figured out again for each project. The market can learn right away and become familiar with everything. Once something has been done multiple times, trust will grow, and the market will be familiar with the process. — *Interviewee 12 (contractor) and Interviewee 15 (client)*

However, it is noted that collaborations are not always positive. Small companies will need each other and will have to build partnerships in order to develop and finance circular innovations. Within these partnerships, each little company prioritizes its own interests and still seeks to maintain a competitive advantage, which may hold back the innovation. — *Interviewee 14 (demolition contractor)*

Improve asset management and storage of historical data in BIM
As mentioned in Section 11.2, it has been stated multiple times that better maintenance policies and monitoring of existing structures are necessary to encourage reuse data [18]. — *Interviewee 5 (engineering consultancy firm and Interviewee 10 (steel manufacturer)* The clients responsible for this are actively working on addressing the issue by implementing BIM (Building Information Modeling). This system allows all relevant information about structures to be stored in a single file format, making it easy to transfer to asset managers. In this way, information on reused components will eventually be just as quickly and easily accessible as for new components, leading to an increase in demand. — *Interviewee 15 (client)*

Make reuse accessible
A frequently mentioned strategy to get the supply chain moving, is to make clear what is possible regarding reuse and making it accessible. This can, for example, be done by gathering all bridges in the Netherlands and their profiles into one 'inventory' to determine what is actually available and subsequently exploring potential applications for these components. By doing so, creative solutions and applications for second-hand steel can be explored. Instead of adopting a complacent attitude and immediately rejecting reuse at the first obstacle, innovative applications for reused steel can be sought, and the options will be clear. — *Interviewee 7 (research firm)*

Furthermore, to create more clarity for the market, it is necessary to map out what can and can not be reused by categorizing different parts of a structure into primary and secondary components. Here, secondary components are parts that can certainly and easily be reused, such as walking routes and railings. By making the process accessible and straightforward, the entire supply chain will become more enthusiastic. — *Interviewee 2 (client)*

This idea is supported by another interviewee, who mentioned that reuse is only worthwhile for them if there are significant benefits *and* the process is easy. Reuse is only considered interesting if it leads to a substantial ENVI/MKI discount. If that is not the case, the easiest option will simply be chosen. So, to encourage reuse, the process must therefore for them be just as easy and clear as using new steel. — *Interviewee 12 (contractor)*

Integrate obtained supply with regular market
To make the choice for reuse as easy as for new steel, reused steel must be included in the same sales chain data [21]. No 'parallel column' should be created for reused steel, but it should be integrated into the regular supply. This way, contractors can order and receive it through traditional channels. — *Interviewee 14 (demolition contractor)*

Find innovative solution for removal of chromium-6
One of the obstacles that even the front runners have not yet fully solved is the fact that much steel in the Netherlands contains heavy metals such as chromium-6. Some time ago, there was no suitable technique to remove the substance. However, there are now several techniques to remove chromium-6, but since these are very expensive, the entire business case for reuse becomes unattractive. Therefore, further research must be conducted to find innovative solutions for removing this harmful coating data [28]. Otherwise, the business case will not be feasible and the market will not follow. — *Interviewee 7 (research firm)*

Deploy reuse as opportunity
Several interviewees mentioned that sustainability is often used as a 'selling point' data [33]. A product becomes more attractive when it is sustainable, which can help justify the potentially higher costs. — *Interviewee 1 (engineering consultancy firm)*

This idea is confirmed by another interviewee. "Reused steel is a material with a story", according to Interviewee 7. It is suggested to place a QR code next to a reused component, allowing people to read about its origin. This could add more value to the material. — *Interviewee 7 (research firm)*

Share knowledge and success stories with the market
When pilots are done and knowledge is gained, it is important to make the market more transparent. Mention which companies have contributed and collaborated, so these companies will become known for their service and successes data [34]. This way, other more hesitant companies that are just starting

out, will be able to trust on the experienced parties and are more likely to engage. This will gradually expand the pool of participating companies. — *Interviewee 14 (demolition contractor)*

Start small
Several people have pointed out the importance of starting small, referring to projects with low risks and lower costs. Due to the lower risks, the supply chain will be more confident and more eager to participate data [22]. If the project turns out to be successful, the next step would be to scale up and gradually the concept of reuse will grow bigger and bigger. — *Interviewee 1 (engineering consultancy firm) and Interviewee 4 (engineering consultancy firm)*

An example is given from a similar situation in the past. The implementation of MKI assessments took years, and for about 15 years, there was a lot of criticism. For a long time, the market did see the value of MKI, partly because MKI values of materials were still unknown and uncertain. Rijkswaterstaat started with pilots, and little by little, it developed further. Currently, many business cases and product innovations have already emerged for several companies from MKI calculations. Reuse could be approached in a similar way. — *Interviewee 4 (engineering consultancy firm)*

11.5.2. Overview of strategies from interviews

The complete overview of all the mentioned strategies is presented in Figure 11.6.

	Strategy	Client	Engineering consultancy firm	Steel manufacturer	Contractor	Demolition contractor	Research institutions and firms
Policy and regulatory	1. Make reuse a mandatory requirement in tenders	2 – 15	1 – 4 – 5	10	3 – 12 – 13 – 16	14	9
	2. Develop contract requirements for circular demolition				16	14	7
	3. Reward the front runners and push the peloton	15			12 – 13 – 16	14	
Cultural and social	4. Deploy reuse as opportunity		1		12	14	7
	5. Choose one focus point	15	4		16		
Technical and operational	6. Create storage locations for obtained supply	2 – 15	4	8 – 10	12 – 13	14	7 – 9
	7. Provide certificates and guarantees	2					9
	8. Make reuse accessible	2	5		12		7
	9. Improve asset management and storage of historical data in BIM	15	5	10			7
	10. Start small	15	1 – 4		12	14	
	11. Integrate obtained supply with regular market					14	
	12. Find innovative solution for removal of chromium-6				3 – 16	14	7
Economic	13. Provide financial incentives	15			12 – 16	14	
Knowledge and skill	14. Share knowledge and success stories with the market	15	4		16	14	
	15. Train the supply chain through partnerships	15	5	8 – 10	12 – 13 – 16	14	

Table 11.6: Strategies mentioned in interviews by different types of stakeholders.

The occurrences of all strategies are summarized in Table 11.7.

Strategy	Occurrence
1. Make reuse a mandatory requirement in tenders	12
2. Develop contract requirements for circular demolition	3
3. Reward the front runners and push the peloton	5
4. Deploy reuse as opportunity	4
5. Choose one focus point	3
6. Create storage locations for obtained supply	10
7. Provide certificates and guarantees	2
8. Make reuse accessible	4
9. Improve asset management and storage of historical data in BIM	4
10. Start small	5
11. Integrate obtained supply with regular market	1
12. Find innovative solution for removal of chromium-6	4
13. Provide financial incentives	4
14. Share knowledge and success stories with the market	4
15. Train the supply chain through partnerships	8

Table 11.7: Strategies and their occurrence with a color gradient from red (low) to green (high).

Explanation
Table 11.7 provides insight into how often each strategy was mentioned across the interviews. Three strategies, namely making reuse a requirement in tenders, creating storage for obtained supply, and training the supply chain, were cited more frequently than others. That the same strategies are proposed by different types of stakeholders suggests that a shared strategic orientation might be present within practice. At the same time, the full range of responses reflects a diverse set of proposed strategies and approaches.

However, these strategies seem not to stand on their own. Some reflect similar underlying concerns and therefore simply counting mentions may not fully capture their systemic meaning. So to better understand how these strategies seem to relate to one another and what they may indicate about the broader context of reuse, the next chapter takes a step back from the individual responses.

Conclusions

In this chapter, the interview data on both obstacles and strategies have been presented. First, a comparison is made between literature and interview data, and these findings may provide new insights within the field of research. Furthermore, two topics stand out as being mentioned by nearly all interviewees, namely the pillars 'Negative attitudes and the 'Availability of steel'. These appear to be related to deeper underlying obstacles, for which a range of strategies have been proposed by the interviewees. The strategies are often interrelated and touch on overlapping issues. To better understand what these connections may reveal about the broader context of reuse, a more interpretive, zoomed-out perspective can be useful. Chapter 12 offers such an analysis by grouping strategies into thematic clusters. This allows for a reflection on the behavioral patterns, institutional dynamics, and other systemic characteristics that influence how reuse takes shape in current practice.

12

Systemic interpretation of interviews

This chapter presents the researcher's interpretation of the interviews. The strategies proposed by stakeholders are clustered into three thematic groups, enabling a systemic analysis of where misalignments may occur across the construction chain. Based on this interpretation, an illustrative road map is developed to show how roles could be more aligned. Lastly, a reflection is given on the possibility that certain doubts about reuse may persist, even when system conditions are improved.

12.1. From strategies to clusters

This chapter builds on the interview data from Chapter 11 and offers an interpretative analysis of the broader behavioral and institutional dynamics behind reuse. Instead of treating each strategy individually, they are grouped into three thematic clusters. The clustering is not directly derived from the data but reflects the researcher's interpretation of what each strategy implies for systemic change. The aim is to move beyond individual suggestions and uncover deeper patterns and misalignments that may hinder the wider adoption of reuse. In short, the clusters are summarized in Table 12.1.

Cluster title	Description	Proposed strategies in interviews
1. Rules and regulations	Strategies focused on formal frameworks such as legislation, tender procedures, and policy tools that structurally anchor reuse.	• 1: Make reuse a mandatory requirement in tenders • 2: Develop contract requirements for circular demolition • 7: Provide certificates and guarantees • 13: Provide financial incentives
2. Collective learning and shared responsibility	Strategies aimed at joint experimentation, knowledge development, and sharing this knowledge across the supply chain.	• 3: Reward the front runners and push the peloton • 4: Deploy reuse as opportunity • 10: Start small • 12: Find innovative solution for removal of chromium-6 • 14: Share knowledge and success stories with the market • 15: Train the supply chain through partnerships
3. Practical and physical logistics	Strategies that address the practical execution of reuse by organizing storage, and integration into the regular market.	• 6: Create storage locations for obtained supply • 8: Make reuse accessible • 9: Improve asset management and storage of historical data in BIM • 10: Start small • 11: Integrate obtained supply with regular market

Table 12.1: Thematic clustering of reuse strategies from interviews.

12.1.1. Cluster 1: Rules and regulations

The first cluster contains strategies aimed at establishing the formal conditions necessary for reuse to take place. The strategies grouped under this cluster focus on, for example, adjusting laws, and contract requirements. This cluster focuses on efforts to make reuse part of an institutional standard rather than a voluntary action or initiative.

Suggested link between strategies and underlying obstacles
According to the interviewees, several underlying obstacles identified in Section 11.3.1 and Section 11.3.2 can possibly be targeted by some of the strategies in this cluster.

- Strategy 1: Make reuse a mandatory requirement in tenders
  This strategy is seen as a way to address confusion about sustainability goals, project time constraints, and the fact that clients often do not ask for reuse.
  "It will contribute to having a clear language to gain more national consensus on how sustainability is pursued" data [17]
  "The political approach needs to be reorganized so that, when it comes down to it, reuse is prioritized" data [23]
  "By legislating the requirement for clients to ask for environmental impact assessments, contractors will see it as an opportunity to profit from it" data [29]
- Strategy 2: Develop contract requirements for circular demolition
  This strategy is seen as a way to overcome contractual limitations and stimulate supply.
  "A first step in obtaining supply is developing contract requirements for circular demolition" data [24]

Blind spots in this strategy landscape
By specifically focusing on regulatory and contractual improvements in this cluster, the data reveals two potentially notable blind spots:

- **Development of a design guideline** for assessing the reuse potential of steel bridge components.
  While the lack of it is acknowledged as an obstacle by multiple interviewees (9 out of 16), none propose the development of such guidelines.
- **Development of mandatory testing standards** for quality certification.
  Although the inability to issue guarantees is recognized as an issue (8 out of 16 interviewees), only by 2 interviewees a proposal was made to establish testing norms for reused components.

The absence of these strategies suggests a deeper gap in the collective awareness of what system change truly requires. It seems that some of the most basic technical regulations for making reuse possible, such as knowing how to assess quality and ensure safety, are not yet part of the strategic thinking in the sector. As long as these blind spots remain, the broader transition toward reuse may continue to face resistance.

12.1.2. Cluster 2: Collective learning and shared responsibility

This cluster focuses on building a culture of learning and collaboration across the supply chain. The strategies grouped here aim to stimulate shared learning, and a willingness to take collective responsibility for innovation and risk. The emphasis lies on forming partnerships and aligning incentives, so that room is created for experimentation and behavioural change. These strategies reflect the understanding that steel reuse requires cooperation across actors, and that it can not be done in isolation.

Suggested link between strategies and underlying obstacles
Several of the strategies in this cluster are seen by interviewees as possible ways to address deeper behavioural and knowledge-related underlying obstacles.

- Strategy 15: Train the supply chain through partnerships
  This is seen as a response to the lack of knowledge and scientific basis regarding reuse.
  "Sharing knowledge and open communication are essential for training the supply chain" data [25]
- Strategy 3: Reward the front runners and push the peloton

This is intended to stimulate market-wide change by recognizing leaders and encouraging the rest of the market. It addresses both lack of scientific basis and client demand.
"A reward system would stimulate them to try and invest more in reuse practices" data [26]
"By rewarding the front runners... the entire chain will eventually be set in motion" data [27]

- Strategy 10: Start small (to build experience and confidence)
  This is proposed as a way to reduce risk and address costs uncertainty.
  "Due to the lower risks, the supply chain will be more confident and more eager to participate" data [22]
- Strategy 12: Find innovative solution for removal of chromium-6
  Targets practical concerns with coating removal, but its innovative framing and gain of knowledge also place it within a broader culture of experimentation.
  "Further research must be conducted to find innovative solutions for removing this harmful coating" data [28]

Blind spots in this strategy landscape
This cluster includes various strategies aimed at knowledge development and behavioural change, and the data also reveals that some proposed ideas lack a connection to the deeper systemic obstacles identified earlier.

- **Deploy reuse as an opportunity**
  This strategy proposes framing reuse as a unique selling point or positive narrative. While promising as a communication tool, it is not linked to any specific underlying obstacle, and risks remaining a surface-level message without institutional reinforcement.
- **Share knowledge and success stories with the market**
  This strategy is intended to increase awareness and recognition for front runners, and may contribute to cultural shifts, but lacks a direct tie to underlying obstacles. As such, it may function more as a symbolic gesture than as a structural lever.

The strategies in this cluster indicate that stakeholders recognize the importance of softer, cultural dimensions of system change, such as narrative and trust. Some cultural strategies remain conceptually valuable, but are practically underdeveloped, such as forming partnerships and reward mechanisms. Furthermore, the strategies reflect an awareness of the importance of shared learning, but how this can be done remains unmentioned. This suggests that while cultural change is recognized, it lacks structured approaches and remains dependent on incidental efforts. As long as this remains the case, reuse may continue to depend on individual leadership rather than collective responsibility.

12.1.3. Cluster 3: Practical and physical logistics

This cluster addresses the logistical and physical obstacles that prevent reuse from being adopted as standard practice. The strategies in this cluster are not about overarching policy or cultural values, but about overcoming practical thresholds in implementation, such as the lack of storage, and integration into the regular market. The aim is to make reuse more accessible in daily project routines by removing practical hurdles.

Suggested link between strategies and underlying obstacles
Several of the strategies in this cluster are seen by interviewees as ways to lower operational obtacles and make reuse more feasible within existing project workflows.

- Strategy 6: Create storage locations for obtained supply (at manufacturers)
  This strategy aims to target the limited availability and logistical accessibility of reusable steel components.
  "Steel manufacturers could perfectly take on this role as they already possess large storage locations" data [20]
  "An additional benefit of having a larger supply is that the reuse process becomes less situation-specific" data [31]
- Strategy 9: Improve asset management and storage of historical data in BIM
  This strategy aims to overcome the lack of information from clients about available components and their technical properties.

"Better maintenance policies and monitoring of existing structures are necessary to encourage reuse" data [18]

- Strategy 10: Start small (to build experience and confidence)
  This may respond to cost uncertainty by encouraging phased experimentation within manageable scopes.
  "Due to the lower risks, the supply chain will be more confident and more eager to participate" data [22]
- Strategy 11: Integrate obtained supply with the regular market
  This strategy intends to streamline reuse within conventional procurement chains, reducing logistical and operational complexity.
  "Reused steel must be included in the same sales chain" data [21]

Blind spots in this strategy landscape
Although the suggested strategies in this cluster may be able to address several practical obstacles, one remains underdeveloped in the proposed ideas by stakeholders:

- **Time pressure in projects**
  Time constraints were repeatedly identified by interviewees as a reason why reuse is avoided. Yet no concrete strategies were proposed to mitigate or manage this issue. This may suggest that time is still treated as a fixed project constraint, rather than a planning variable that could be reshaped to accommodate reuse.

This blind spot may reflect a broader reluctance to adapt project workflows or planning structures to reuse conditions. The strategies proposed by stakeholders rarely address project planning or time management explicitly. Instead of rethinking routines, reuse is often expected to fit into conventional systems where speed and predictability dominate. As long as that expectation persists, reuse may continue to depend on exceptional effort rather than becoming part of standard practice.

12.1.4. Key takeaways: systemic misalignments
Looking across the clustered strategies, a pattern emerges, namely that reuse is not primarily hindered by a lack of ambition, willingness, awareness. These elements are to a certain extent present across the sector. However, one thing that remains less developed, is alignment at the system level. Many proposed strategies reflect good intentions, but often address surface-level symptoms rather than the deeper structures that potentially shape everyday practices. This disconnect may limit the effectiveness and scalability of reuse efforts. Based on this interpretative analysis, three core misalignments within the current system are identified.

1. Awareness without ownership of action
The lack of strategies aimed at developing design guidelines and testing standards indicates that some of the most basic technical conditions for reuse, such as quality assurance and standardized assessment, are not yet fully embedded in the sector's strategic thinking. This may limit both the credibility and scalability of reuse efforts. While these underlying obstacles are widely recognized, the absence of structural responses suggests a system where ambition is not consistently translated into concrete development. It also points to a lack of ownership as no clear actor seems to take the lead in addressing these technical foundations, which may explain why little progress is being made.

2. Cultural willingness lacks structural support
Many proposed strategies show that stakeholders increasingly value the cultural dimensions of system change, such as trust, shared language, and leadership. However, these strategies often remain abstract or loosely defined. Ideas such as forming partnerships or offering rewards are conceptually strong but lack concrete follow-up. Moreover, there is little clarity on how shared learning is to be organized. This suggests that while the need for cultural change is broadly recognized, its operationalization is weak. Without clearer frameworks or shared responsibilities, cultural strategies may risk remaining symbolic rather than systemic.

3. Reuse is expected to fit into unchanged routines
Stakeholder strategies rarely address project planning or time management directly. As a result, existing routines, which are mainly focused on speed and predictability, remain largely intact. Reuse is

typically expected to fit into these conditions, rather than prompting a rethinking of the routines themselves. This may suggest a broader reluctance to adjust systemic processes to better accommodate circular practices. As long as this expectation persists among stakeholders, reuse is likely dependent on exceptional effort and may remain difficult to embed in standard workflows.

The three observations outlined above suggest that reuse may be held back by a fragmented and insufficiently aligned system. This means that, the technical, cultural, and procedural elements needed to support reuse are present in parts, but seem to remain disconnected in practice. Responsibilities are diffuse, routines stay unchanged, and promising ideas often lack operational follow-up. As a result, reuse may remain difficult to implement within existing structures. Each of the identified misalignments, seems to point to areas where current practices fall short of supporting reuse at scale. While no single actor can probably address these gaps alone, the proposed strategies offer concrete indications of where change could be initiated and how different roles in the chain might be involved.

To explore this further, a possible synthesis of the practical strategies is presented in the form of a non-prescriptive road map. This is not a fixed solution, but one way to visualize how various actors across the construction chain might begin to realign system conditions in support of reuse. The road map builds on the interview material and strategic ideas discussed earlier, translating them into potential actions, responsibilities, and points of leverage.

12.2. Illustrative road map

The road map presented in Figure 12.1 builds on the clustered interpretation of stakeholder strategies in the previous section. Rather than offering a definitive solution or sequence of steps, this road map outlines one possible interpretation of how different stakeholders might contribute to improving conditions for reuse. Its structure is based on the mismatches between stakeholder responsibilities, technical challenges, and systemic incentives. While it can be used to prescribe action, it primarily aims to illustrate where coordination could be improved and which roles might be required to reduce systemic misalignments. In doing so, the road map sketches a possible ‘ideal situation’ of responsibilities and support structures that could enable reuse to become a viable daily practice.

Where the clusters helped reveal how reuse is constrained by a mix of regulatory fragmentation, behavioral hesitations, and logistical complexity, the road map brings these threads together. It also builds on the insight that the problem is not simply that reuse is difficult, but that it is currently expected to operate within a system that was not designed to support it.

A full overview of the action points per stakeholder, based on the link between strategies and obstacles, can be found in Appendix K. These action points served as input for the composition of the road map and clarify how suggested strategies could translate into concrete roles.

Explanation for road map of example ideal situation

The starting point is a policy adjustment from the government. A desired situation could be to first introduce CO2 taxation (indirect legislation) to take a small step towards more reuse adoption, and still keep it feasible. This taxation can serve as an incentive for clients to ask for reuse, which will potentially drive supply and may lead to small pilot projects. Lessons learned from these pilots can eventually lead to scaling up and increase the knowledge of the entire chain. Meanwhile, front runners can invest in solving the remaining obstacles and help the rest of the supply chain gain confidence in reuse. Once the system is aligned thus supply of steel is sufficiently large, direct legislation can be introduced, making reuse mandatory in tenders. This will probably create a huge demand, and may lead to a surge in the market and widespread adoption of reuse.

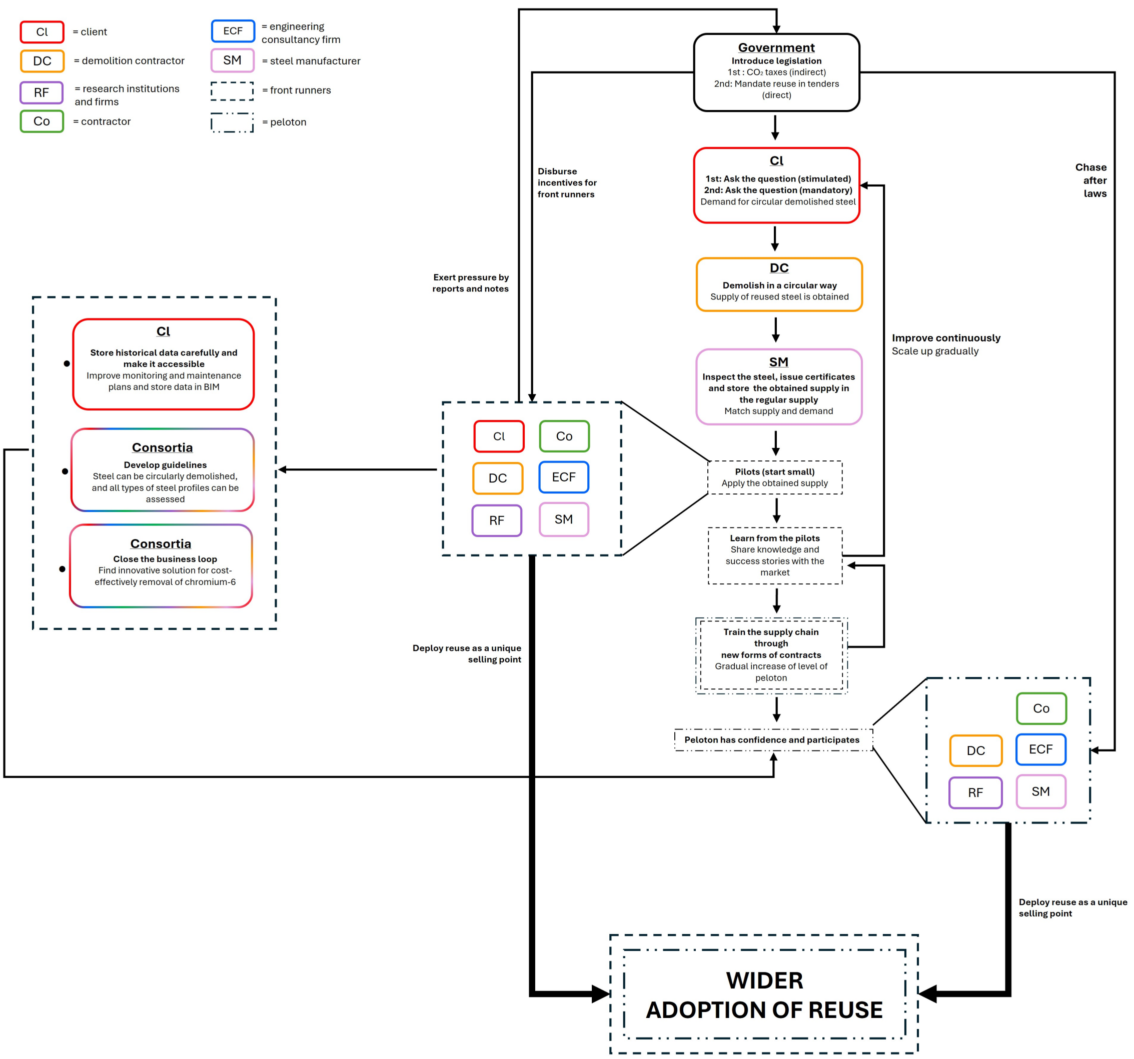


Figure 12.1: Developed illustrative road map to show aligned actions across the construction industry.

12.3. Inherent doubts rooted in the nature of reuse

The previous sections explored how reuse could be supported by aligning systemic roles, incentives, and routines. However, even in the potentially more aligned system, some doubts and disadvantages regarding reuse may remain. These concerns appear to be rooted not in the absence of policy or planning, but in the nature of reuse itself.

The interviews suggest that certain reservations persist, which are not easily resolved through improved coordination alone. These concerns seem to reflect underlying characteristics of reuse, such as aesthetic preferences and functional expectations. These factors may not be decisive, but can potentially influence the decision-making. Even in a more aligned system, these inherent doubts may cause hesitation or limit the extent to which stakeholders are willing to embrace reuse in practice.

- Reuse may lead to higher maintenance costs, since imperfections in second-hand components may require more frequent repairs or inspections. “An existing bridge will always perform worse in terms of maintenance compared to a new one, which makes reuse less preferable” data [35].
- Professional preferences and interests can also play a role in reducing enthusiasm, if components do not align with aesthetic expectations. “Architects often prefer to see something new and may therefore be opposed to the reuse of steel” data [36].
- The reduced remaining service life of reused components presents a practical limitation. “A reused steel profile typically offers a shorter remaining service life compared to a new one” data [37].
- Despite financial incentives for front runners, these will probably not be enough to cover all costs. several interviewees suggest these are inadequate. “Governmental funds will never be enough to cover all costs” data [38].
- Regulations are not dynamic and usually becoming stricter over time. “Standards and regulations are dynamic” data [39].
- The unique character of many bridge structures may complicate reuse as no standardization of designs is possible. “The reuse of bridge components may be less impactful compared to the reuse of, for example, overpasses” data [40].

Rather than expecting all doubts to disappear, it may be more realistic to acknowledge the boundaries they reveal. In this light, reuse does not need to eliminate all concerns, but it does require the stakeholders to recognize and work with imperfection, rather than expecting a perfect fit.

→ Understanding and awareness about these inherent concerns may help stakeholders acknowledge that flexibility is needed to make reuse more acceptable in daily practice.

12.4. Technical suggestions to support confidence

In addition to systemic coordination and awareness of reuse limitations, this research has explored several technical measures that may contribute to increased confidence in reuse applications. These suggestions do not directly address the deeper systemic misalignments, but may provide practical options to reduce perceived technical uncertainty. The suggestions are based on insights gained throughout the research process in Chapter 10 and reflect possible ways to make reuse more acceptable under current conditions.

- **Monitoring in service:** While design guidelines, as described in Chapter 10, support the initial assessment of reused components, additional assurance could be derived from in-service monitoring. Such monitoring may provide data on actual performance over time, offering insights into remaining strength or fatigue life.
- **Reducing value/consequence class:** Section 3.1 shows that reuse often targets high-value applications, which tend to involve higher consequence classes. Applying reused components in lower-risk contexts, such as non-critical structural parts, could present an alternative use case with lower consequences.
- **Reducing additional lifetime:** New civil engineering works are typically designed for long service lives. In cases where reused components do not meet such requirements, applying them in short-

term or temporary structures may offer a more feasible match between material properties and design expectations.

- **Reducing corrosivity class:** Corrosion remains a concern for reused components, so application in low-corrosivity environments, such as indoor or protected structures, combined with protective strategies like coatings or cathodic protection, may reduce degradation risks and make certain reuse scenarios more viable.
- **Axle load limitation:** In bridge applications, limiting axle loads may reduce peak stresses and fatigue damage. This may be particularly relevant in contexts where components have known histories or are used in light-traffic settings.
- **'LEGOliseren':** Reuse does not necessarily require intact replication of entire structures. Dismantling specific components, such as plates or profiles, and reusing them individually may allow their properties to be re-evaluated and applied in new contexts. This modular use can help remove problematic welds, which often represent fatigue-prone areas.

Conclusions

This chapter has shown that many of the previously identified underlying obstacles to reuse are not merely practical or motivational in nature, but reflect deeper misalignments in how responsibilities, routines, and expectations are currently structured. The added value of this interpretation and thus systemic lens lies in highlighting how well-intended strategies may remain disconnected from the institutional context in which they are expected to function.

Across the three thematic clusters, regulatory frameworks, collective learning, and logistical enablement, a recurring pattern emerged, namely that awareness is present, but action lacks ownership. Furthermore, cultural willingness exists, but structural reinforcement is lacking. Lastly, reuse is promoted in the chain, but still expected to conform to traditional construction routines. These misalignments seem to explain why reuse often depends on exceptional efforts rather than being embedded in standard practice.

The illustrative road map offers one possible way to realign roles and responsibilities, and to encourage more coordination across the construction chain. Besides to that, the technical suggestions presented in this chapter may offer practical means to reduce uncertainty, especially in projects where risk and performance are key concerns. Still, not all doubts can probably be resolved through alignment alone. Some reservations appear to be rooted in the nature of reuse itself. Acknowledging and recognizing these inherent boundaries, rather than attempting to eliminate them, may help set more realistic expectations and enable greater flexibility in practice for stakeholders.

In that light, the path toward wider adoption may lie not in removing every obstacle, but in fostering systemic alignment, working with imperfection, and creating shared space for experimentation and thus learning.

Part IV

Research outcome

13
Discussion

This chapter outlines the discussion of the research. First, the findings from the research are placed within the existing body of literature. Then the limitations and shortcomings of the study are addressed. Next, the aspect of validity is discussed, so whether the research has measured what it intended to measure. Finally, the practical implications and usability of the research are discussed.

13.1. Placing findings within the existing body of literature

This study began with a literature review that identified five overarching obstacles to the adoption of steel reuse, namely the sourcing difficulties, the absence of design standards, lack of EU regulations, economic uncertainties, and behavioral resistance (Densley Tingley et al., 2017; Dunant et al., 2018; Halonen et al., 2024; Hart et al., 2019; Kanyilmaz et al., 2023). These obstacles span technical, regulatory, economic, and cultural domains.

13.1.1. Contribution of design guideline

Firstly, the technical obstacle of absence in suitable design standards for verifying whether reused components have reuse potential is addressed. As discussed in Chapter 4.2, current Eurocodes are written for constructing with new materials and profiles. The newly developed NTA 8713 might seem promising, but it is limited to the assessment of components reused from buildings (CEN-members, 2023). It does not offer procedures for fatigue-prone components such as OSDs, leaving structural engineers unable to evaluate their structural integrity and approve them for safe reuse.

This thesis responds directly to that gap. The design guideline developed in Chapter 10 provides a structured, three-step approach tailored to infrastructure components. By embedding fatigue knowledge, damage modeling, and practical reuse logic into a single workflow, the guideline transforms sustainability ambitions into a technical procedure.

Although the guideline was developed using the Freebrug as a case study, its underlying logic is broadly applicable to other structural elements within steel bridges. As discussed in Section 10.3, the methodology can be scaled up to larger bridges by incorporating more refined fatigue models, such as FLM4 (CEN-members, 2024). Furthermore, the three-step structure of: documentation, damage assessment, and reuse mapping, can also be applied to other components such as truss members, girders, or pylons. While these components may differ in geometry or fatigue sensitivity, the same structured workflow can enable engineers to evaluate the reuse potential in a systematic way.

In short, the guideline offers a structured, component-level approach to assessing the reuse potential of infrastructural components. While developed for OSDs, the underlying logic can support more tailored reuse decisions across various types of bridge components.

13.1.2. Contribution of interview insights

Where Subsection 13.1.1 focused on addressing the technical domain, this Subsection returns to the broader set of obstacles identified in the literature (Densley Tingley et al., 2017; Dunant et al., 2018; Halonen et al., 2024; Hart et al., 2019; Kanyilmaz et al., 2023). Through interviews, it explores whether and how these technical, regulatory, economic, and behavioral challenges manifest in practice.

The interview data confirms that some of these theoretical obstacles are also strongly present in practice. Notably, the two most frequently mentioned obstacles among interviewees, namely the 'Availability of steel' and 'Negative attitudes', correspond directly with two of the obstacles previously identified in literature, namely respectively the difficulty of sourcing suitable steel components (Kanyilmaz et al., 2023), and the reluctance or hesitancy within the construction ecosystem to adopt reuse practices (Hart et al., 2019). These findings suggest an alignment between theory and practice. Moreover, both obstacles appeared for all stakeholder types in the construction supply chain, confirming that they are not specific concerns but shared across the chain.

However, the interviews also reveal some divergence between theoretical insights and real-world perceptions. For instance, while the literature emphasizes the 'Lack of design rules' as a core technical limitation (Kanyilmaz et al., 2023; Nethercot, 2012), only about half of the interviewees identified this issue unprompted. Similarly, although 'Costs uncertainty' is theoretically seen as an obstacle (Cheng et al., 2024; Dunant et al., 2018), the significance in practice appears to vary. While some stakeholders cited costs as a decisive issue, others described it as manageable. So for these two obstacles, there is sometimes agreement and sometimes disagreement between theory and practice. This suggests that such obstacles may not be universally experienced, but are instead shaped by individual roles and organizational priorities. It may also reflect a selective internalization of some of these theoretical issues within daily practice, for example, when some challenges are acknowledged but might be perceived as not urgent.

The most notable deviation between theory and practice concerns the 'Lack of EU regulations', such as the absence of a CE marking process for reused components (Condotta and Zatta, 2021; Halonen et al., 2024). Although this is cited as a legal obstacle, the majority of interviewees either did not mention it or considered it a concern. This discrepancy could add to the existing literature that there might be limited awareness among stakeholders. It may also suggest that legal challenges are viewed as less immediate than technical or logistical hurdles, and are not prioritized in daily project routines.

In addition to confirming and contesting existing literature, the interview data contribute to the body of knowledge by identifying 14 additional obstacles that were not captured in the initial literature review. These include issues such as contractual limitations, the time taken for reuse considerations in projects, and the lack of responsible stakeholders for issuing quality certificates. These findings highlight a potential gap in the literature, suggesting that empirical practices in steel reuse may be evolving more rapidly than theoretical insights currently reflect.

Moreover, the interviews yielded a substantial set of suggestions of possible strategies to overcome reuse obstacles, which is an area that remains underdeveloped in current literature. While some contributions in the literature briefly address enabling conditions for reuse (Dunant et al., 2018), there is currently no comprehensive, empirically grounded overview of actionable strategies for the different domains.

Among the 15 proposed strategies, three strategies were mentioned most frequently. These are: 'make reuse a requirement in tenders' (12 out of 16 times), 'create storage locations for obtained supply' (10 out of 16 times), and 'train the supply chain through partnerships' (8 out of 16 times). These were proposed by different types of stakeholders across the chain, and are notable for targeting three distinct levels of the reuse challenge: institutional anchoring, logistical feasibility, and behavioral development.

That the same strategies are proposed by different types of stakeholders suggests that a shared strategic orientation might be present within practice. This practical insight adds to the current body of literature, which has so far paid limited attention to strategy formation. Furthermore, it adds to the literature that stakeholders are not only aware of obstacles, but also appear to be actively formulating responses.

Taken together, the interview findings extend the literature in three ways. By confirming well-documented obstacles, by supplementing additional obstacles, and by offering a range of strategic proposals. More fundamentally, based on the frequency counting, they show that the sector may already be converging on common solutions.

13.1.3. Contribution of interpretative analysis

The interpretative analysis in Chapter 12 builds upon the interview data to identify deeper misalignments that may limit the widespread adoption of steel reuse. By clustering the proposed stakeholder strategies into three overarching themes, namely rules and regulations, collective learning and shared responsibility, and practical and physical logistics, the analysis may move beyond surface-level obstacles and offers a systemic perspective on reuse practices.

This perspective complements and extends the existing literature in several ways. Firstly, the thematic clustering confirms findings from earlier research suggesting that reuse is not constrained by technical feasibility alone, but also by a lack of systemic integration across the supply chain (Densley Tingley et al., 2017; Hart et al., 2019).

One example of this is the 'Lack of design guidelines', which is frequently identified in the literature as an obstacle to reuse in infrastructure projects (Kanyilmaz et al., 2023). The findings of this thesis deepen this observation by showing that the issue is not merely the absence of such guidelines, but also the lack of action and ownership over their development. Although the need for a guideline is widely acknowledged, no actor assumes responsibility for its creation. This dynamic, referred to in the analysis as 'awareness without ownership of action', adds a behavioral and governance dimension to what is often framed as a purely technical problem.

Secondly, the strategies within the 'collective learning' cluster elaborate on existing academic work addressing cultural resistance in the construction sector. Prior studies describe the sector as risk-averse and conservative (Hart et al., 2019), and call for increased openness to innovation. This research identifies two additional dynamics: (1) The tendency of symbolic strategies, such as promoting reuse through storytelling or rewarding front runners, remain unanchored in practice. (2) The absence of mechanisms for structured learning across projects and organizations. These findings align with earlier calls to build institutional capacity for reuse (Densley Tingley et al., 2017).

Thirdly, the practical logistics cluster highlights a structural obstacle that is underrepresented in existing literature, namely the impact of project time pressure. Whereas previous studies have primarily focused on technical issues such as certification and quality control (Condotta and Zatta, 2021; Halonen et al., 2024), the interview data suggest that rigid timelines and conventional planning practices may significantly constrain opportunities for reuse. Few stakeholders propose strategies that address or challenge these time structures, indicating that reuse is largely expected to conform to existing routines. This adds specificity to broader concerns raised in literature about institutional inertia and conservative practices (Hart et al., 2019), suggesting that time pressure may function as a key mechanism through which such inertia is maintained in daily practice.

Finally, the findings from the interviews suggest a more reflective way of framing reuse. While much of the literature presents reuse as a desirable goal to be enabled through technical and regulatory solutions, the interview data reveal that certain concerns may be rooted in the nature of reuse. Rather than expecting all doubts to disappear, it may be more realistic to recognize that reuse requires stakeholders to work with imperfection. This observation aligns with critical reflections on circular design (Fivet, 2022; Yeung et al., 2017), which emphasize the importance of awareness and the flexibility needed throughout the process.

13.2. Limitations

Due to the need to complete the research within the intended timeframe, several limitations were encountered. These are listed and explained below.

Applicability of Load Model 1

For the development of the FE model, the traffic load was modeled using Load Model 1 (LM1). A limitation of this modeling approach is that this load model is applicable for bridges with a span $L > 11$ [m], which is the typical length of a truck. Since the span of the case study bridge is shorter, the application of LM1 in its standard form results in a conservative estimate of the traffic load. Although there is the possibility to apply a reduction factor (α) to calibrate the load model to actual traffic conditions and the specific characteristics of the bridge, this was not implemented in the present analysis due to time limitations. As a result, the applied traffic loading may overestimate the actual effects, but ensures a conservative assessment.

Use of Fatigue Load Model 3
The research uses the single vehicle model FLM3 for fatigue modeling, which assumes $F = 120$ [kN] and does not distinguish between different types of vehicles. This is a conservative approach, but FLM3 can be used for the direct verification of designs through a simplified method. If a more accurate representation of the various types of lorries is available, FLM4 may yield more accurate results.

Subjectivity in corrosivity class choice
To determine corrosion damage, a corrosion class must be selected in the calculation model that best fits the environment of the donor structure. These classes are based on qualitative environmental descriptions and not on measurable values. This introduces a subjective element that may have influenced the results. A conservative class can always be selected, but this may lead to over-dimensioning.

Lack of measurements for corrosion
For the case study, corrosion damage was determined solely based on analytical models. Real-time measurements, such as actual thickness loss, would enable more reliable assessments of the condition of the steel. These measurements could contribute to the design guideline in two ways. First, they could be directly implemented in the FE model as reduced cross-sections, leading to more accurate structural simulations. Second, they could serve as validation data for the calculation model used in the guideline. If real-world values are available, incorporating them helps to increase the reliability of future scenario predictions.

Uncertainty in amount of fatigue cycles
The estimation of fatigue damage was based on a rough approximation of the number of cycles. The number of heavy vehicles likely varied throughout the structure's lifespan. Furthermore, estimates for future use are also sensitive to errors and must be made with care, for example, through extrapolated traffic data.

Neglecting effects of previous bridge operation
The fatigue analysis focused solely on the current static function of the bridge. However, the case study concerns a previously movable bridge, meaning it has experienced decades of opening and closing cycles prior to decommissioning. Although the movable mechanism is now out of operation, the historical use may have introduced additional fatigue damage. This previously repeated movement was not explicitly included in the model, and that may introduce uncertainty in the residual fatigue capacity.

Log-log scale sensitivity S-N curve
Fatigue damage is determined using the number of load cycles and compared to the remaining capacity from the S-N curve. The S-N curve is presented on a log-log scale, which is sensitive to reading errors. The researcher minimized this by plotting a secondary log scale next to the axes, but even small reading errors can significantly impact the calculated number of cycles because of the logarithmic nature.

Effect of technical measures unknown
The proposed technical measures that could enable a certain reuse application have only been mentioned. There has been no calculation of the second-order effects of these measures. An example of this is axle load limitation; applying this would mean that heavy vehicles would need to take a detour around a bridge, and this detour would result in additional emissions compared to the original route. The question then is whether there is actually any environmental benefit being achieved. In short, the effects of implementing the technical measures have not been mapped out, which is a shortcoming.

Number of interviewees
The number of interviewees is $N = 16$. The goal was to interview at least $N = 2$ stakeholders per type, with a preference for $N \geq 3$. For demolition contractors, only one interviewee was found. Including more demolition contractors could have increased the reliability of the conclusions. For steel manufacturers and research institutions, $N = 2$, so an additional interview would have increased certainty as well.

13.3. Validity

Single case study

The design guideline was developed based on a single case study. It should be noted that analyzing a single case study does not guarantee that the findings are universally applicable, as the results reflect the outcome under specific conditions. Other structures may behave differently, and conclusions should therefore be applied with caution. Ideally, a broader set of bridges would be analyzed to support the development of a general guideline. This limits the generalizability and may reduce the practical applicability of the conclusions. This practical applicability and potential for using it beyond the current case is described in more detail in Section 10.4.

Intentional and unintentional interviewee bias

Interviewee selection introduces bias. This bias is partly intentional, as the goal was to interview professionals with relevant expertise to ensure depth of discussion. However, unintentional bias may also be present, namely because people interested in reuse are more likely to accept interview requests. As a result, the participation pool may be disproportionately positive toward reuse, limiting the validity of general conclusions about the entire supply chain. Nevertheless, the interviewees' insights into other actors in the chain can still be used.

Blind spots in stakeholder strategies

The strategies proposed by stakeholders during the interviews were grounded in their own professional context and understanding of reuse. While these insights provide essential input for possible approaches, they may not always reflect a full awareness of the reasons why certain reuse efforts have not yet gained traction. This is understandable, as actors typically operate within the boundaries of their own roles and responsibilities. As such, some potential underlying systemic interdependencies may remain outside their direct view. To mitigate this, the thesis developed an interpretative, system-oriented lens to place individual strategies within a broader context and to explore where misalignments occur.

Subjectivity in assessing data saturation

Determining when data saturation is reached is not fully objective. The researcher conducts and analyzes the interviews and must assess whether new information is still being generated. This introduces a subjective element. Although this was minimized by focusing purely on observations and avoiding interpretation, subjectivity may still influence the analysis.

Influence of order of interviews

Another point of discussion is whether the order of the interviews may have influenced the results. The researcher's knowledge grew gradually during the process, possibly enabling more relevant follow-up questions later on. Although efforts were made to minimize this by adhering to the interview protocol, the potential influence can not be ruled out entirely.

Dynamic nature of topic

Moreover, reuse is a 'hot topic' and dynamic issue. It is possible that new developments occurred in the field during the eight-week interview period. This may have influenced interviewee responses, making it difficult to compare early interviews with later ones. The researcher did not observe major changes, but this can not be stated with 100% certainty.

Influence of inconsistent prompting on frequency

In the analysis, obstacle frequencies were counted to identify the most frequently mentioned ones. However, some obstacles were explicitly prompted as they were previously identified in the literature research, while others were not. This unequal prompting may have distorted the frequency data. As a result, the counting method may not fully reflect the true occurrences of obstacles, which affects the conclusions.

13.4. Discussion on modeling assumptions and simplifications

Neglecting arc radius (R)

In the models, the arc radius was neglected, meaning that the transitions between profiles were modeled with sharp 90-degree angles rather than smooth curves. This simplification can lead to artificial local stress concentrations at the corners, which would not occur in reality. The presence of a bend in reality ensures a gradual stress distribution, resulting in lower local stress peaks. As a result, stresses may have been overestimated in certain areas, particularly at the locations where fatigue details were evaluated. The fatigue stress range, $\Delta\sigma$, was determined based on the normal stress in the bottom flange of the stiffener, which implies that the analysis may locally include overstated stress values. For increased accuracy, it could be advisable to model the arc radius explicitly.

Neglecting specific loads
Several loads were omitted from the modelling process, namely temperature loads, braking and acceleration forces, and wind loads. For temperature loads, it was assumed that thermal fluctuations would not significantly influence the results, due to limited environmental temperature variations. However, including this load would offer a more realistic approximation of the system's behaviour. Braking and acceleration forces can locally become governing, but due to insufficient data, they were not considered in this study. As for the wind load, there is currently no information available regarding its magnitude in a reuse scenario, which justifies its exclusion from the analysis.

Neglecting lateral steel rods
The two steel rods located at the edges of the deck, which originally provided stability during the bridge lifting process, were not modeled. This simplification is not expected to affect the results, as the bridge is no longer operational in terms of opening and closing. The forces are now transferred directly from the deck downward into the foundation and not upward through the steel rods, meaning they do not contribute to the analysed load paths.

Neglecting the upper plate of the cross beam
A simplification was applied in modelling the cross beams by representing them as U-profiles composed of three plates, excluding the upper fourth plate. This results in slightly reduced thickness at these locations compared to the real structure, leading to a minor underestimation of stiffness and strength. While including the upper plate would improve accuracy, this type of cross beam is rarely used today. The U-profiles used in the model are more representative of common practice, making this simplification acceptable for drawing broader conclusions regarding reuse.

Profiles modeled as plate elements
Modelling the structural profiles as 2D plate elements does not negatively affect the final results. On the contrary, 2D elements allow for analysis of 3D force transfer, which aligns well with the real structural behaviour. If the profiles had been modeled as 1D elements, this would not have represented the actual force distribution accurately and could have led to incorrect results.

Welds modeled as rigid links
Welds were modeled as rigid links in the analysis. In reality, welds possess finite stiffness and can fail under certain conditions. Additionally, this assumption may suppress local stresses and deformations. While not entirely accurate, this simplification is expected to have only a minor effect on the overall results and is therefore considered acceptable within the scope of this study.

13.5. Implications and usability

This thesis aimed to advance the understanding of how the adoption of reused steel bridge components can be increased. The research delivers practical tools that can be applied across various segments in the supply chain.

The study presents calculation models that assess the condition of steel components, from which practical reuse applications can be derived based on identified damage patterns. Both the individual calculation models and the complete design guideline can be used by other researchers. They can expand on these outcomes and provide further recommendations that could stimulate steel reuse even more. In addition, design teams and structural engineers can adopt the guideline as a reference when designing with reused steel components. It offers guidance to support design decisions and contributes to standardization.

Furthermore, the insights provided into common obstacles and strategies to overcome them can inspire and inform supply chain stakeholders. In particular, the interpretative analysis of the interview data through a system lens has offered additional insight by highlighting how reuse challenges may be shaped by interactions between regulatory frameworks, culture, and operational routines. Rather than treating these as isolated issues, the analysis makes visible how they seem to be interconnected across different layers of the construction system. This perspective complements the strategy overview by clarifying the broader context in which these strategies are proposed and might operate.

The developed road map reflects this shift in focus, namely rather than prescribing one fixed path, it visualises how actors might begin to realign their roles and responsibilities in response to systemic obstacles. It serves as a practical, non-prescriptive tool to identify possible actions across the chain.

In addition, the study shows that rather than aiming to eliminate all concerns, it may be more constructive to acknowledge the inherent doubts that come with working with reused steel. Reuse requires stakeholders to accept a degree of imperfection, and awareness of these boundaries can support a shift to a more flexible mindset. The technical measures proposed in this study may help to strengthen confidence, and can be used as convincing arguments or supporting evidence when promoting reuse initiatives.

Overall, this research offers a foundation and concrete tools to bring reused steel bridge components closer to becoming a common and adopted practice in the Dutch construction industry.

14 Conclusion and recommendations

This chapter presents the conclusions drawn from the study. Conclusions are formulated per sub-question as well as an answer to the main question. Based on the research findings, a set of practical recommendations is provided. Finally, suggestions for future research are outlined.

In this thesis, the following main research question is posed:

“What is needed to stimulate the adoption of steel bridge component reuse among stakeholders in the Dutch construction industry?”

This question is answered by breaking it down into different parts in line with the Sub-Questions (SQ). Subsequently, these findings are synthesized to provide a comprehensive answer to the main research question at the end of this chapter.

14.1. Answer to sub-questions

The first sub-question that is posed is:

- ***SQ1: What is the state of the art of the adoption of reuse practices in the construction industry?***

The literature reveals that the adoption of steel reuse receives attention due to a need for circularity, but is not as straightforward due to obstacles. Five commonly cited obstacles span technical, regulatory, economic, and cultural domains. Firstly, sourcing of the steel is difficult because material properties are sometimes uncertain. It should be available at the right place and time with the proper quality, meaning supply and demand must align. Secondly, there is currently a lack of design standards tailored to the assessment of steel reuse from infrastructure. All existing Eurocodes focus on designing with new steel, and while the NTA 8713 offers guidance for buildings, it excludes fatigue-sensitive bridge components. Thirdly, there is a lack of regulations within the European Union, such as CE marking procedures, as marketing products without this mark is not possible. Fourthly, there is cost uncertainty as reuse is often more expensive due to testing, disassembly, and unpredictability in logistics. Finally, reuse requires trust and coordination throughout the supply chain, yet many stakeholders remain hesitant. This behavioral resistance is often rooted in concerns over quality and unfamiliarity with reuse processes. These aspects are later in SQ4 discussed in the empirical findings from stakeholder interviews.

One of the obstacles identified in the literature review concerns the lack of technical guidelines for assessing steel components from existing infrastructure. To address this gap, the next part of the study conducted engineering research to explore how existing damage in such components can be evaluated. The focus was on understanding the types of damage that reused steel bridge components may already contain, and how this damage can be reliably assessed.

This leads to answering the next sub-question:

- ***SQ2: What types of damage can a steel bridge component already have that should be taken into account when assessing its reuse potential?***

The damage a steel component can sustain depends on the type of component and its use history. To allow for a focused yet broadly applicable assessment, the study first zoomed out to examine general bridge types in the Netherlands and then narrowed the focus to movable bridges. Within this selection, the Orthotropic Steel Deck (OSD) was chosen for further investigation of reuse potential. This component was selected because it is commonly used in the Netherlands, offers high structural efficiency, meaning it can carry significant loads relative to its self-weight, and is therefore considered a promising candidate for potential reuse.

Based on the literature, the most critical failure mechanisms for OSDs are corrosion, fatigue, and the combination of these, which is also known as Corrosion Fatigue. Corrosion is described as the process in which oxygen deteriorates the outer layer of the steel. Fatigue is the progressive degradation of a component caused by fluctuating stress over an extended duration of time. The synergistic effect of both mechanisms may lead to greater damage than if they occur separately. These failure mechanisms should be considered to assess the condition of the steel after its first service life.

This is applied to a case study, namely the Freebrug in Oude Pekela, which is a movable bridge with an OSD. This is a common bridge type in the Netherlands and is therefore chosen to make the findings more widely applicable. To even increase relevance, two types of Finite Element Models of OSDs are developed, namely one with continuous troughs (with cut-out holes in cross beams) and one with discontinuous troughs (without cut-out holes in cross beams). Both types occur in practice, making it relevant to include both and not choose between the two. After applying all relevant loads and the described future scenarios, it is found that both model types meet stress requirements even under the most severe corrosion scenario, corresponding to a thickness reduction of $\Delta t = 0.71$ [mm].

For fatigue, it turns out that the critical details are the welds between the deck plate and trough, and between the cross beam and trough. All calculated damage numbers are below 1 for a future scenario of an additional 50 [y]. The calculated damage numbers make it possible to assess whether a proposed future use scenario is technically feasible or not. For Corrosion Fatigue, the studied details again comply and show damage numbers below 1. A notable finding is that the details between cross beam and trough show a significant increase in damage number, namely 39% for continuous troughs and even 319% for discontinuous troughs. Although these values only apply to this case study and loading scenario, they indicate a substantial increase in damage, which is considered in the development of a design guideline for reuse.

From this case study, it is discovered what is required to determine the condition of steel from infrastructure, and how, based on the damage, intended future use scenarios are feasible or not. Now the next sub-question will be answered, which is:

- ***SQ3: What are the key steps in assessing the technically safe reuse potential of steel bridge components?***

The design guideline consists of three steps:

1. Initial data: Collect all original data of the donor structure at the time of delivery.
2. Service life data: Determine the condition of the steel by mapping the damage caused by the identified mechanisms using calculation models.
3. Future possibilities: Translate the identified damage into a feasible reuse scenario.

If the intended future scenario is not feasible, several technical measures can be taken to reduce the required performance. These are: placing the component in a lower corrosivity class environment, reducing the future number of service years, limiting axle loads, changing the function of the component and ‘LEGOliseren’. The application of these measures reduces the technical performance, potentially enabling reuse.

These findings from the case study demonstrate that it is possible to systematically assess the condition and remaining capacity of reused steel components from infrastructure, even when damage from corrosion, fatigue, or their combination is present. To do so in a consistent and transparent manner, this thesis proposes a structured design guideline that guides engineers through the process of technical reuse assessment.

This leads to the answer to the main research question from the Structural Engineering perspective. To stimulate the adoption of reused steel bridge components from a Structural Engineering perspective, a reproducible method is needed to assess their remaining performance. The three-step design guideline developed in this thesis, focusing on initial documentation, damage assessment, and mapping of feasible reuse scenarios, provides such a method and addresses the technical obstacle to reuse.

Besides to that, also other obstacles in other domains are identified in the literature research. This literature-based identification is supplemented with interview data from practice. This brings the study to the next sub-question:

- ***SQ4: What obstacles to the adoption of steel reuse are perceived by stakeholders, and what strategies do they propose in response?***

A total of 16 interviews are conducted with various actors in the supply chain: clients, engineering firms, steel manufacturers, contractors, demolition contractors, and research institutions. The interviews uncover 19 distinct obstacles to reuse. Two of these, namely the 'Availability of steel' (mentioned in all 16 interviews) and 'Negative attitudes' (mentioned 13 out of 16 times), are mentioned most frequently and appear across all stakeholder types. These two are encountered consistently by stakeholders because they are related to other perceived obstacles according to the interview data. For example, 'Negative attitudes' is mentioned in relation to 'Cost uncertainty' and a 'Lack of knowledge of clients'. Similarly, 'Availability of steel' is associated with underlying issues such as 'Client does not ask for it' and 'Contractual limitations'. Therefore, these two most frequently mentioned obstacles have deeper roots and are referred to as pillars with associated underlying obstacles. The overview of relations is visualised in Figure 14.1.

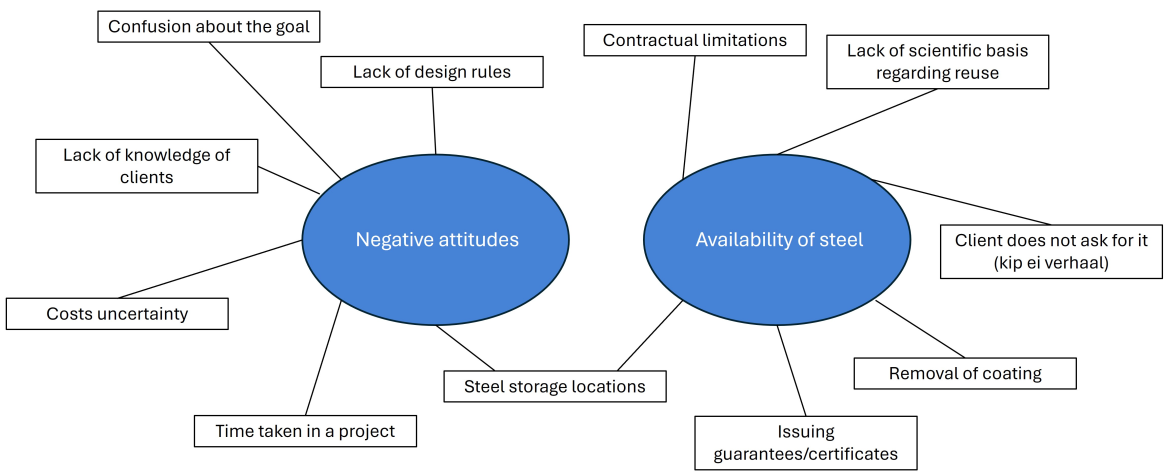


Figure 14.1: Overview of which underlying obstacles (circular shaped) are related to two pillars (rectangular shaped) according to interview data.

In addition to this analysis, the interview data offer a point of comparison with the theoretical obstacles identified in the literature. The interviews confirm that several of the theoretical obstacles identified in literature are also experienced in practice. Notably, two obstacles, namely the 'Availability of steel' and 'Negative attitudes', are most frequently mentioned and occur across all stakeholder types. This confirms that reuse is not only hindered by technical limitations, but also by behavioural aspects.

At the same time, the interview data reveal that not all theoretical obstacles are equally present in practice. For example, the obstacle 'Lack of design guidelines' is widely emphasised in academic work, but mentioned by only approximately half of the interviewees (9 out of 16 times). Similarly, while 'Cost uncertainty' is often highlighted in literature as a hurdle, interviewees present mixed views (mentioned 7 out of 16 times). For some, costs are a decisive issue, while others consider them manageable, especially when reuse aligns with sustainability ambitions.

The most notable divergence between theory and practice concerns the obstacle 'Lack of EU regulations' (mentioned 5 out of 16 times). Nine interviewees disagreed with this literature-based obstacle. This may indicate either a lack of awareness or a tendency to view legal challenges as more abstract or distant compared to technical and logistical ones.

Having identified and structured the obstacles to steel reuse, both from literature and practice, the next step in this study is to explore how these obstacles might be addressed according to interviewees. Across the interviews, 15 reuse strategies are proposed, ranging from technical measures to coordination mechanisms and cultural interventions. Among the 15 proposed strategies, three strategies were mentioned most frequently. These are: 'make reuse a requirement in tenders' (12 out of 16 times), 'create storage locations for obtained supply' (10 out of 16 times), and 'train the supply chain through partnerships' (8 out of 16 times). These were proposed by different types of stakeholders across the chain, and are notable for targeting three distinct levels of the reuse challenge: institutional anchoring, logistical feasibility, and behavioral development.

That the same strategies are proposed by different types of stakeholders suggests that a shared strategic orientation might be present within practice. At the same time, the full range of responses reflects a diverse set of proposed strategies and approaches. However, these strategies seem not to stand on their own. Some reflect similar underlying concerns and therefore simply counting mentions may not fully capture their systemic meaning. So to better understand how the strategies interrelate, a step back was taken.

The strategies were clustered into three overarching themes:

- Rules and regulations
- Collective learning and shared responsibility
- Practical and physical logistics

This leads to the last sub-question:

- ***SQ5: How can the identified obstacles and strategies be understood in relation to broader systemic patterns in the construction industry?***

The clustering enables a more interpretative analysis through a system lens, aimed at uncovering deeper misalignments that prevent steel reuse from becoming daily practice. The added value of this systemic perspective is that it places the interview data within a broader understanding of how the sector is currently organised. Rather than treating these as isolated problems, the clustered interpretation of stakeholder strategies suggests that obstacles may result from deeper misalignments between policy, responsibility, and project routines.

This interpretative analysis reveals a pattern: awareness is present, but action may lack ownership. Furthermore, cultural willingness exists, but structural reinforcement is sometimes lacking. Lastly, reuse is often promoted in the chain, but still may be expected to conform to traditional construction routines. These misalignments help explain why reuse often depends on exceptional efforts rather than being embedded in standard practice. A shared understanding of how these systemic patterns constrain adoption may help move the discussion beyond isolated strategies, towards a more sector-wide change.

An illustrative road map, as depicted in Figure 14.2, is developed to offer one possible way to realign roles and responsibilities, and to encourage more coordination across the construction chain.

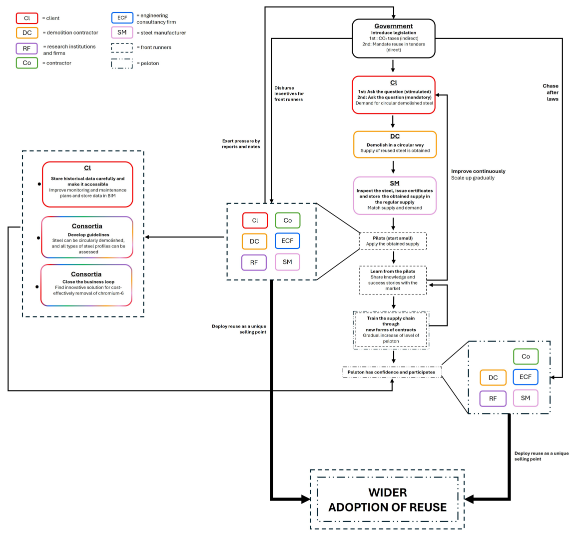


Figure 14.2: Developed illustrative road map to show aligned actions across the construction industry.

A final contribution of the analysis is a subtle shift in how reuse may be understood. Rather than presenting it as a goal that can be fully enabled, several stakeholders express that certain doubts are rooted in the nature of reuse, even regardless of technical reassurance. This view aligns with more critical reflections in recent literature and suggests that reuse adoption also requires space to deal with imperfections, rather than eliminating all concerns entirely.

This leads to the final conclusion from a Construction Management and Engineering perspective to the main research question. To stimulate the adoption of reused steel bridge components from a management perspective, reuse appears to require a shared sense of ownership, institutional learning mechanisms, and adjustments in project routines. In addition, the findings suggest that awareness of imperfection and flexibility may contribute to wider adoption of reuse into practice.

14.2. Answer to main research question

The findings reveal that stimulating reuse requires progress on both technical and systemic levels. From a Structural Engineering perspective, a central obstacle is the lack of standardized procedures to assess the safety and performance of reused components from infrastructure. This technical gap was addressed in the form of a case study, in which OSDs were analyzed using Finite Element Models. Based on this, a three-step design guideline was developed to assess reuse potential in a consistent and reproducible way. This guideline includes: collecting original data, mapping damage conditions, and evaluating feasible future use scenarios. These findings demonstrate that even with damage from prior use, structural components can be reassessed for reuse, and thereby addressing the technical gap to adoption.

However, technical feasibility alone does not ensure adoption. A broader analysis, based on literature and interviews with 16 stakeholders, indicates that reuse is influenced by institutional, behavioral, and logistical factors. Two most frequently encountered obstacles, namely 'Availability of steel' and 'Negative attitudes', emerged as pillars. These are not isolated issues, but are often related to a wider set of underlying obstacles. Stakeholders proposed a broad range of reuse strategies, spanning different domains. When these suggested strategies are interpreted through a systemic lens and clustered thematically, several patterns become apparent. Firstly, awareness is present, but action appears to lack ownership. Furthermore, cultural willingness exists, yet structural support is sometimes lacking. Lastly, reuse is actively encouraged, but often expected to conform to conventional construction practices. So to stimulate the adoption of reused steel bridge components from a management perspective, reuse appears to require a shared sense of ownership, institutional learning mechanisms, and adjustments in project routines. In addition, the awareness of imperfection and flexibility may contribute to wider adoption of reuse into practice.

While the technical and systemic findings stem from different disciplinary domains, they appear to be closely interrelated in practice. Without a method to reliably assess technical performance, reuse may continue to be perceived as risky. Conversely, even with such a method, broad adoption is unlikely if system conditions do not align. This thesis therefore shows that addressing the technical gap is necessary, but not sufficient. Adoption also requires alignment across the supply chain, ranging from clients who ask for reuse, to engineers who can justify it, and contractors who are logistically prepared to implement it. By integrating both technical and managerial perspectives and acknowledging reuse as a broader system transition, this thesis contributes to making reuse a more realistic and actionable option within the Dutch construction industry.

14.3. Recommendations

A number of recommendations are provided based on the conclusions found in this research. In addition, suggestions for future research are made.

14.3.1. Practical recommendations based on this thesis

- For components that initially appear technically unsuitable for reuse, it is recommended to explore combinations of the found technical measures instead of relying on single solutions. A combined approach may increase feasibility while preserving as much structural value as possible.
- Furthermore, to assess the technical reuse potential of steel bridge components in a safe and consistent manner, it is advised to apply the 3-step guideline developed in this thesis. This guideline includes initial documentation, damage modeling, and evaluating feasible reuse scenarios.
- Since the analysis revealed that reuse initiatives are often fragmented and lack clear ownership, it is recommended to assign explicit responsibilities early in the process. Appointing a coordinator to check up on these responsibilities could improve shared ownership and coordination across stakeholders. For example, the identified ambiguity around quality control responsibilities, especially concerning certification of reused components, is advised to be clarified early on. Based on interview data, assigning certification responsibility to the manufacturer may be a workable solution.
- Because the lack of alignment between actors limits coordinated action, it is recommended to support this alignment with visual tools such as road maps. These can possibly clarify roles, make abstract ambitions actionable, and stimulate joint planning across the chain.
- As reuse is often driven by a small group of front runners and cultural willingness is present but not institutionalized, it is advised to stimulate sector-wide behavioral change through structured knowledge sharing. This may include documenting pilot results, and supporting open learning platforms.
- Given that reuse adoption is often constrained by tight project schedules and standardized routines assuming new materials, it is recommended to adapt project procedures to better accommodate reuse. This could include incorporating flexibility in timelines, and starting the project schedule with reuse in mind.
- Since multiple stakeholders expressed concerns related to the imperfections of reused components, even when technically validated, it is advised to increase awareness of this limitation chain-wide. Accepting and acknowledging a degree of imperfection, rather than trying to eliminate all uncertainty, may enable broader adoption in practice.
- Because technical evaluations alone do not determine reuse feasibility, it is recommended that future assessments also consider regulatory, logistical, and behavioral boundaries early in the design process. This broader scope can increase the chance that reuse is actually implemented in real projects.
- To get the chain moving and lower entry barriers, it is advised to initiate pilot projects with realistic scopes in which profit is not the primary objective. These pilots should not aim to be perfect, but rather serve as structured learning experiments that help build routine and reduce perceived risk.

14.3.2. Recommendations for future studies

- Future research could explore how the proposed guideline performs when applied to components with actual measured damage, such as ultrasonic testing, or infrared scanning. This could help validate whether the calculations align with physical conditions.
- It is recommended to investigate the environmental trade-offs of reuse strategies, because the proposed technical measures involve side effects. For example, if axle loads are reduced, the emissions caused by heavy traffic detours should be considered in life cycle assessments.
- Another suggestion is to analyze the relationship between reuse and repair. Currently, the design guideline focuses on acceptance or rejection based on damage, but in practice, repair could open up additional reuse opportunities that would otherwise be dismissed.
- Survey-based research could complement this thesis by capturing a broader and possibly more neutral perspective of the stakeholders, especially to test whether socially desired answers are given.
- Future research could examine whether similar systemic patterns and misalignments emerge in other reuse contexts. In this way, the broader applicability of the clustering logic developed in this thesis can be assessed. This would help determine whether the three thematic clusters represent system-wide conditions for reuse adoption, or whether they are specific to the context of this thesis.
- Future research could further examine the systemic misalignments identified in this thesis by exploring how they occur in practice, and what exact mechanisms underlie.
  1. Awareness without ownership of action: It could be explored how actors perceive responsibility for initiating reuse efforts, and how awareness relates to actual decision-making.
  2. Cultural willingness without structural reinforcement: Research could focus on how reuse-related knowledge and intentions could be more followed-up witin organisations
  3. Reuse expected to fit into unchanged project routines: Another possible direction to investigate is how project planning schedules and timelines can be shaped in order to give space for reuse.
- Finally, it could be valuable to share the findings of this research with the original interviewees. A follow-up discussion could help expand upon the conclusions and may lead to additional insights based on their reflections and feedback.

Specific FE modeling recommendations

- Future modeling efforts could benefit from expanding the use of local mesh refinement to other fatigue-sensitive details not studied in this thesis, especially if more diverse bridge geometries are considered.
- In cases where real-life measurements of corrosion or fatigue damage are available, it is recommended for future studies to validate the FE model based on actual data to improve reliability. This could reduce conservatism and strengthen confidence in reuse scenarios.
- Since rigid links were used to model welds, a recommendation for future studies is to explore how different modeling assumptions influence local stress concentrations, especially since welds are governing for fatigue performance.

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Part V

Appendices

A

Double degree explanation

This thesis has been written as part of a Double Degree programme, in which Civil Engineering (CE) with the track Structural Engineering, and Construction Management and Engineering (CME) with the graduation domain Projects & People are combined.

There are parts of this thesis that contribute to both degrees and serve the objectives of both programmes. In addition, there are also sections specific to each of the degrees to ensure the required level of depth is maintained. The distinction is given in Table A.1. Below an explanation is given.

Link to report (click on number)	Both	CE	CME
Chapter 1 Introduction	✓		
Chapter 2 Methodology	✓		
Part I Literature review on reuse practices by exploring obstacles	✓		
Part II Technical reuse potential of steel bridge components		✓	
Part III Stakeholder perspectives on achieving adoption of reuse by the supply chain			✓
Part IV Research outcome	✓		

Table A.1: Overview of distinction between Master's programmes.

The overlapping from Part I provide a general literature-based foundation. This analysis reveals a range of obstacles in various areas, technical, economic, and regulatory, that prevent stakeholders from fully embracing the use of reused steel components.

To address one of these obstacles, namely the technical aspect of a lack of design rules, the next part of this thesis focuses on the CE Master's degree. In Part II, a step-by-step design guideline is proposed for assessing reuse potential from a structural engineering perspective.

Having tackled one major obstacle, the remaining question is how the other ones can also be reduced, so that actors across the supply chain are stimulated to participate in reuse practices. Part III of this thesis focuses on the various stakeholders in the supply chain and is aligned with the CME Master's degree.

Finally, in Part IV, the conclusion wraps up all findings and ties both sides together with the ultimate goal of broader adoption of reuse practices among the supply chain.

B

Corrosivity classes

Corrosivity category[a]	Corrosivity	Typical environments — Examples[b]	
		Indoor	Outdoor
C1	Very low	Heated spaces with low relative humidity and insignificant pollution, e.g. offices, schools, museums	Dry or cold zone, atmospheric environment with very low pollution and time of wetness, e.g. certain deserts, Central Arctic/Antarctica
C2	Low	Unheated spaces with varying temperature and relative humidity. Low frequency of condensation and low pollution, e.g. storage, sport halls	Temperate zone, atmospheric environment with low pollution (SO_2 < 5 μg/m^3), e.g. rural areas, small towns Dry or cold zone, atmospheric environment with short time of wetness, e.g. deserts, subarctic areas
C3	Medium	Spaces with moderate frequency of condensation and moderate pollution from production process, e.g. food-processing plants, laundries, breweries, dairies	Temperate zone, atmospheric environment with medium pollution (SO_2: 5 μg/m^3 to 30 μg/m^3) or some effect of chlorides, e.g. urban areas, coastal areas with low deposition of chlorides Subtropical and tropical zone, atmosphere with low pollution
C4	High	Spaces with high frequency of condensation and high pollution from production process, e.g. industrial processing plants, swimming pools	Temperate zone, atmospheric environment with high pollution (SO_2: 30 μg/m^3 to 90 μg/m^3) or substantial effect of chlorides, e.g. polluted urban areas, industrial areas, coastal areas without spray of salt water or, exposure to strong effect of de-icing salts Subtropical and tropical zone, atmosphere with medium pollution
C5	Very high	Spaces with very high frequency of condensation and/or with high pollution from production process, e.g. mines, caverns for industrial purposes, unventilated sheds in subtropical and tropical zones	Temperate and subtropical zone, atmospheric environment with very high pollution (SO_2: 90 μg/m^3 to 250 μg/m^3) and/or significant effect of chlorides, e.g. industrial areas, coastal areas, sheltered positions on coastline
CX	Extreme	Spaces with almost permanent condensation or extensive periods of exposure to extreme humidity effects and/or with high pollution from production process, e.g. unventilated sheds in humid tropical zones with penetration of outdoor pollution including airborne chlorides and corrosion-stimulating particulate matter	Subtropical and tropical zone (very high time of wetness), atmospheric environment with very high SO_2 pollution (higher than 250 μg/m^3) including accompanying and production factors and/or strong effect of chlorides, e.g. extreme industrial areas, coastal and offshore areas, occasional contact with salt spray

Figure B.1: Description of environments related to the estimation of corrosivity categories (CEN-members, 2012b).

C

Corrosivity rates

Corrosivity category	Corrosion rates of metals r_{corr}				
	Unit	Carbon steel	Zinc	Copper	Aluminium
C1	g/(m^2·a)	$r_{corr} \leq 10$	$r_{corr} \leq 0,7$	$r_{corr} \leq 0,9$	negligible
	µm/a	$r_{corr} \leq 1,3$	$r_{corr} \leq 0,1$	$r_{corr} \leq 0,1$	—
C2	g/(m^2·a)	$10 < r_{corr} \leq 200$	$0,7 < r_{corr} \leq 5$	$0,9 < r_{corr} \leq 5$	$r_{corr} \leq 0,6$
	µm/a	$1,3 < r_{corr} \leq 25$	$0,1 < r_{corr} \leq 0,7$	$0,1 < r_{corr} \leq 0,6$	—
C3	g/(m^2·a)	$200 < r_{corr} \leq 400$	$5 < r_{corr} \leq 15$	$5 < r_{corr} \leq 12$	$0,6 < r_{corr} \leq 2$
	µm/a	$25 < r_{corr} \leq 50$	$0,7 < r_{corr} \leq 2,1$	$0,6 < r_{corr} \leq 1,3$	—
C4	g(m^2·a)	$400 < r_{corr} \leq 650$	$15 < r_{corr} \leq 30$	$12 < r_{corr} \leq 25$	$2 < r_{corr} \leq 5$
	µm/a	$50 < r_{corr} \leq 80$	$2,1 < r_{corr} \leq 4,2$	$1,3 < r_{corr} \leq 2,8$	—
C5	g/(m^2·a)	$650 < r_{corr} \leq 1\,500$	$30 < r_{corr} \leq 60$	$25 < r_{corr} \leq 50$	$5 < r_{corr} \leq 10$
	µm/a	$80 < r_{corr} \leq 200$	$4,2 < r_{corr} \leq 8,4$	$2,8 < r_{corr} \leq 5,6$	—
CX	g/(m^2·a)	$1\,500 < r_{corr} \leq 5\,500$	$60 < r_{corr} \leq 180$	$50 < r_{corr} \leq 90$	$r_{corr} > 10$
	µm/a	$200 < r_{corr} \leq 700$	$8,4 < r_{corr} \leq 25$	$5,6 < r_{corr} \leq 10$	—

NOTE 1 The classification criterion is based on the methods of determination of corrosion rates of standard specimens for the evaluation of corrosivity (see ISO 9226).

NOTE 2 The corrosion rates, expressed in grams per square metre per year [g/(m^2·a)], are recalculated in micrometres per year (µm/a) and rounded.

NOTE 3 The standard metallic materials are characterized in ISO 9226.

NOTE 4 Aluminium experiences uniform and localized corrosion. The corrosion rates shown in this table are calculated as uniform corrosion. Maximum pit depth or number of pits can be a better indicator of potential damage. It depends on the final application. Uniform corrosion and localized corrosion cannot be evaluated after the first year of exposure due to passivation effects and decreasing corrosion rates.

NOTE 5 Corrosion rates exceeding the upper limits in category C5 are considered extreme. Corrosivity category CX refers to specific marine and marine/industrial environments (see Annex C).

Figure C.1: Corrosion rates for the first year of exposure for different categories (CEN-members, 2012b).

D

Corrosion time exponent values

	Steel		Zinc		Copper		Aluminium	
	B1	**B2**	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**
***b* values**	0,523	0,575	0,813	0,873	0,667	0,726	0,728	0,807
***t* (years)**								
1	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
2	1,437	1,490	1,757	1,831	1,588	1,654	1,656	1,750
3	1,776	1,881	2,443	2,609	2,081	2,220	2,225	2,427
4	2,065	2,219	3,087	3,354	2,521	2,736	2,743	3,061
5	2,320	2,523	3,701	4,076	2,926	3,217	3,227	3,665
6	2,553	2,802	4,292	4,779	3,304	3,672	3,685	4,246
7	2,767	3,061	4,865	5,467	3,662	4,107	4,123	4,808
8	2,967	3,306	5,423	6,143	4,003	4,525	4,544	5,355
9	3,156	3,537	5,968	6,809	4,330	4,929	4,951	5,889
10	3,334	3,758	6,501	7,464	4,645	5,321	5,346	6,412
11	3,505	3,970	7,025	8,112	4,950	5,702	5,730	6,925
12	3,668	4,174	7,540	8,752	5,246	6,074	6,104	7,428
13	3,825	4,370	8,047	9,386	5,534	6,438	6,471	7,924
14	3,976	4,561	8,547	10,013	5,814	6,793	6,829	8,413
15	4,122	4,745	9,040	10,635	6,088	7,142	7,181	8,894
16	4,263	4,925	9,527	11,251	6,355	7,485	7,527	9,370
17	4,401	5,099	10,008	11,863	6,618	7,822	7,866	9,839
18	4,534	5,270	10,484	12,470	6,875	8,153	8,200	10,304
19	4,664	5,436	10,955	13,072	7,127	8,480	8,530	10,764
20	4,791	5,599	11,422	13,671	7,375	8,801	8,854	11,218

Figure D.1: Time exponents (b values) for standard metals per year of exposure (CEN-members, 2012b).

	Steel		Zinc		Copper		Aluminium	
	B1	B2	B1	B2	B1	B2	B1	B2
25	5,384	6,365	13,694	16,611	8,559	10,349	10,416	13,432
30	5,923	7,069	15,882	19,477	9,666	11,814	11,814	15,561
35	6,420	7,724	18,002	22,283	10,713	13,213	13,307	17,622
40	6,885	8,340	20,067	25,038	11,710	14,558	14,666	19,627
45	7,322	8,925	22,083	27,749	12,668	15,857	15,979	21,585
50	7,737	9,482	24,058	30,423	13,590	17,118	17,252	23,500
60	8,511	10,530	27,902	35,672	15,347	19,541	19,701	27,225
70	9,225	11,506	31,627	40,810	17,009	21,855	22,041	30,831
80	9,893	12,424	35,254	45,856	18,593	24,079	24,291	34,339
90	10,521	13,295	38,797	50,822	20,113	26,229	26,466	37,764
100	11,117	14,125	42,267	55,719	21,577	28,314	28,576	41,115

Figure D.2: Time exponents (b values) for standard metals per year of exposure (CEN-members, 2012b).

E

Results without cut-out holes

Critical location verification without cut-out holes

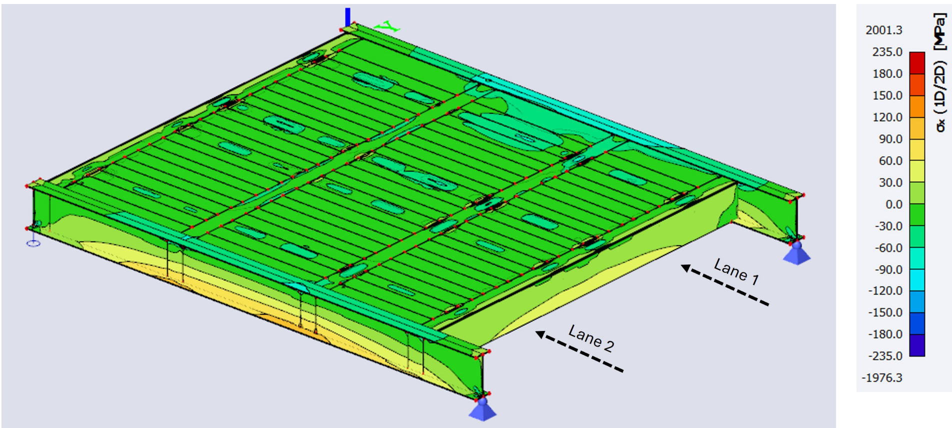


Figure E.1: Critical location verification without cut-out holes in SCIA Engineer - ULS traffic lane 1 maximum.

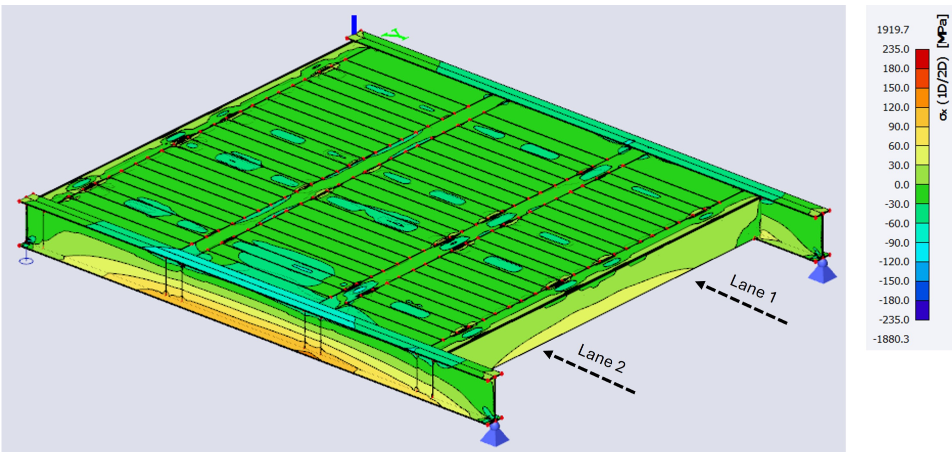


Figure E.2: Critical location verification without cut-out holes in SCIA Engineer - ULS traffic lane 2 maximum.

Corrosion verification (ULS2) without cut-out holes in SCIA Engineer.

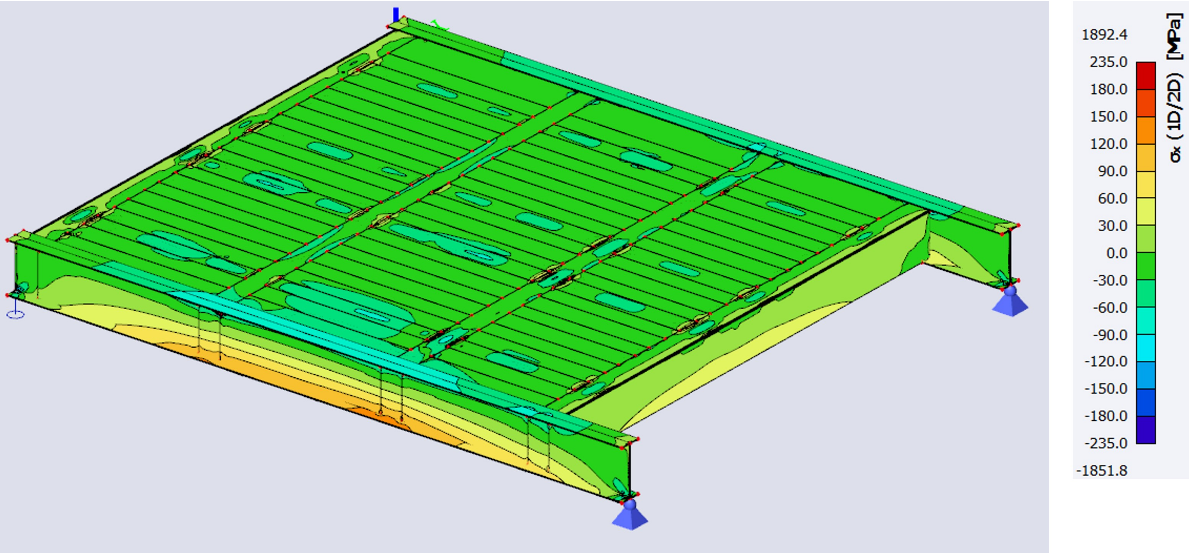


Figure E.3: 3D stress verification with reduced cross sections for ULS2 in SCIA Engineer.

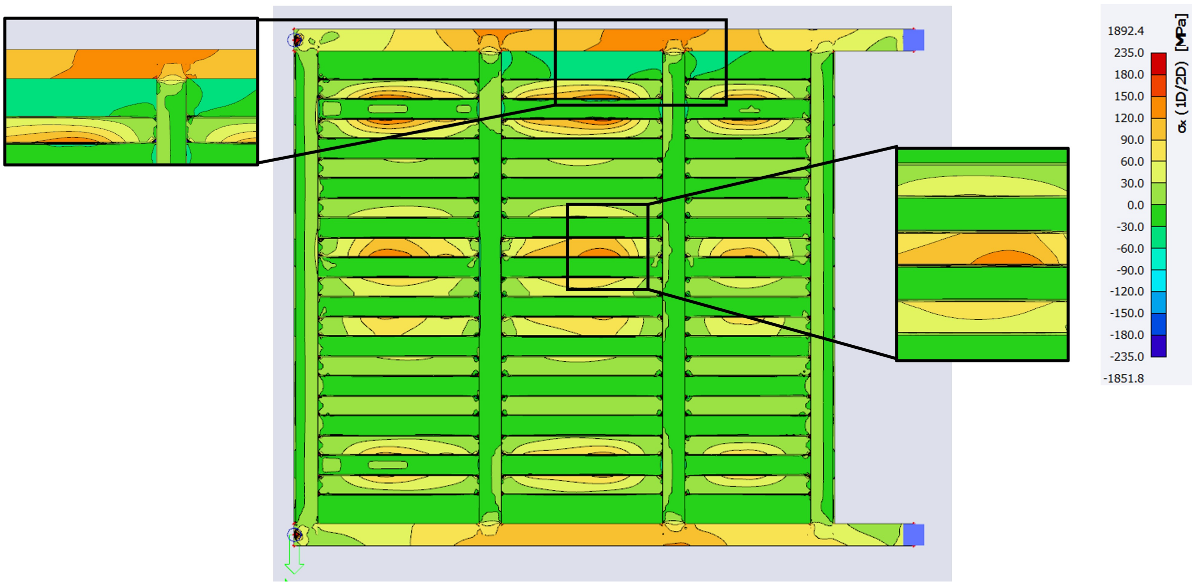


Figure E.4: 3D stress verification bottom view with zoomed-in details of main girder (2) and trough 7 in SCIA Engineer.

Fatigue critical location verification without cut-out holes

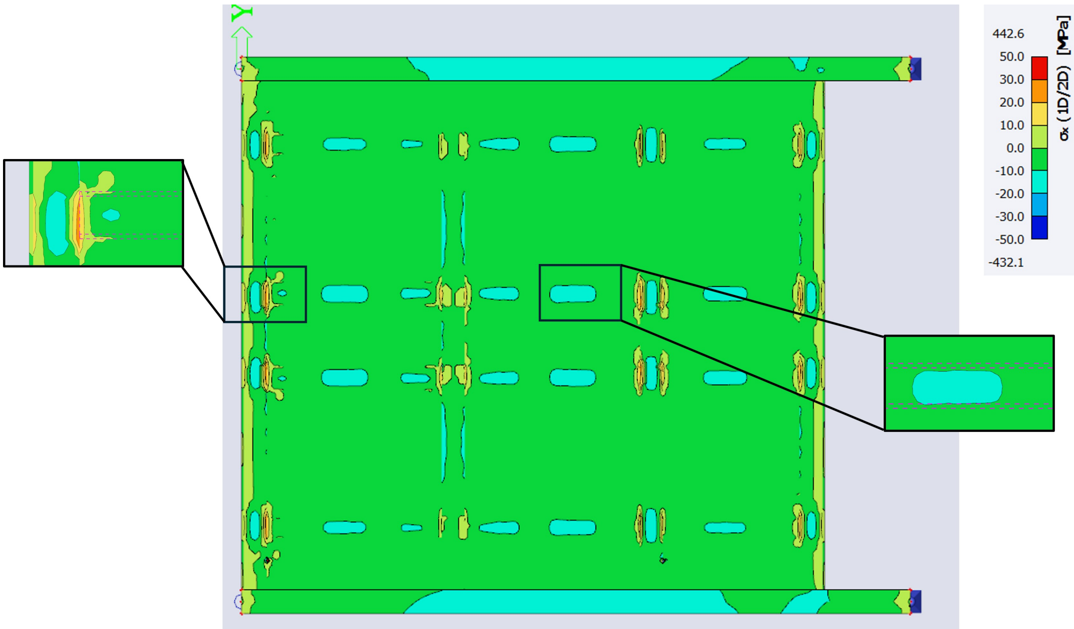


Figure E.5: Stresses due to SLS fatigue loading, zooming in on possible governing details for trough to deck weld in SCIA Engineer.

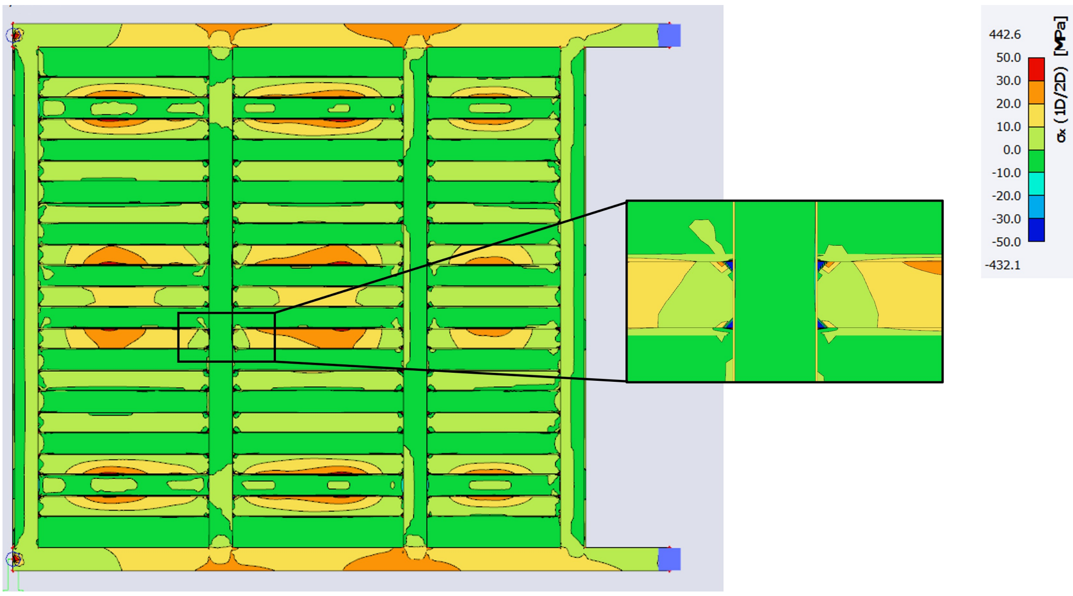


Figure E.6: Stresses due to SLS fatigue loading, zooming in on governing detail for discontinuous trough to cross beam joint in SCIA Engineer.

F

Lower bound approach

Ondergrensbenadering

D.1 Ondergrensbenadering voor materiaaleigenschappen

Als alleen het bouwjaar van het donorbouwwerk bekend is en de staalsoort onbekend, dan mogen de materiaaleigenschappen (vloeigrens en treksterkte) met een ondergrensbenadering worden bepaald volgens tabel D.1. Als de staalsoort wel bekend is, kunnen deze materiaaleigenschappen met bijlage C worden bepaald.

Tabel D.1 — 1955-heden: ondergrensbenadering voor de treksterkte en vloeigrens

Periode	Aanname staalsoort voor ondergrens		f_y N/mm²	f_u N/mm²
1955-1972	Gewalst staal H		235	335
1972-1990	Fe 310 / Fe 33	$t \leq 40$ mm	200	310
		40 mm $< t \leq 100$ mm	180	280
1990-1997	Fe 360 / FeE 235 [a]	$t \leq 40$	235	360
		$40 < t \leq 100$	215	340
		$100 < t \leq 250$	175	320
1997-2005	S235	$t \leq 40$	235	360
		$40 < t \leq 100$	215	340
		$100 < t \leq 250$	175	320
2005-heden	S235	$t \leq 40$	235	360
		$40 < t \leq 100$	215	340
		$100 < t \leq 250$	175	320

[a] NEN-EN 10025:1991 geeft nog Fe 310-0. Omdat NEN 6770:1991 deze staalsoort niet noemt, wordt aangenomen dat Fe 310-0 in deze periode niet is toegepast in gebouwen.

(CEN-members, 2023)

Tabel D.2 — 1955-heden: ondergrensbenadering voor de breuktaaiheid

Periode	**Aanname staalsoort voor ondergrens**	**Kerfslagwaarde (K_v)**
1955-1972	**V 1035 deel IV**	
	Gewalst staal H	Geen aanname mogelijk, beproeven volgens bijlage E
1972-1990	**Euronorm 25-72**	
	Fe 310 / Fe 33 [a]	Geen minimale kerfslagwaarde, beproeven volgens bijlage E
	Fe 360 A	Geen minimale kerfslagwaarde, beproeven volgens bijlage E
	Fe 430 A	Geen minimale kerfslagwaarde, beproeven volgens bijlage E
	Fe 510 BFN	28 J bij +20 °C
1990-1997	**NEN-EN 10025:1991**	
	Fe 360 B [a]	27 J bij +20 °C
	Fe 430 B	27 J bij +20 °C
	Fe 510 B	27 J bij +20 °C
	NEN-EU 113:1986	
	FeE 255 KG t/m FeE 460 KG	40 J bij −20 °C
1997-2005	**NEN-EN 10025:1993**	
	S235JR [a]	27 J bij +20 °C
	S275JR	27 J bij +20 °C
	S355JR	27 J bij +20 °C
	NEN-EN 10113-2:1993/ NEN-EN 10113-3:1993	
	S460N/S460M	40 J bij −20 °C
2005-heden	**NEN-EN 10025-2:2004**	
	S235JR [a]	27 J bij +20 °C
	S275JR	27 J bij +20 °C
	S355JR	27 J bij +20 °C
	S450J0	27 J bij 0 °C
	NEN-EN 10025-3:2004/ NEN-EN 10025-4:2004	
	S460N/S460M	40 J bij −20 °C

[a] Indien zowel staalsoort als staalkwaliteit onbekend is, deze waarde aanhouden.

(CEN-members, 2023)

Tabel D.3 — 1955-heden: ondergrensbenadering maximumkoolstofequivalent (CEV)

Periode	**Aanname staalsoort voor ondergrens**	**Maximum-CEV**	
1955-1972	**V 1035 deel IV**		
	Gewalst staal H Gewalst staal Qm37	Niet gegeven	
1972-1990	**Euronorm 25-72**		
	Fe 310 / Fe 33 Fe 360 / Fe 37 Fe 430 / Fe 44 Fe 510 / Fe 52	Maximum-CEV niet beschikbaar	
1990-1997	**NEN-EN 10025:1991**	**$t \leq 40$**	**$40 < t \leq 150$**
	Fe 360 BFU / Fe 360 BFN Fe 360 C / Fe 360 D1 / Fe 360 D2 Fe 430 B t/m Fe 430 D2 Fe 510 B t/m Fe 510 DD2	0,35 0,35 0,40 0,45	– 0,38 0,42 0,47
	NEN-EU 113:1986	**$t \leq 35$**	**$35 < t \leq 100$ [a b]**
	FeE 255 KG FeE 255 KW FeE 255 KT		0,54 0,54 0,52
	FeE 285 KG FeE 285 KW FeE 285 KT		0,55 0,55 0,53
	FeE 315 KG FeE 315 KW FeE 315 KT		0,56 0,56 0,55
	FeE 355 KG FeE 355 KW FeE 355 KT	0,60	0,62 0,60 0,60
	FeE 390 KG FeE 390 KW FeE 390 KT		0,71
	FeE 420 KG FeE 420 KW FeE 420 KT		0,75

(CEN-members, 2023)

Periode	**Aanname staalsoort voor ondergrens**	**Maximum-CEV**		
	FeE 460 KG FeE 460 KW FeE 460 KT			0,80
1997-2005	**NEN-EN 10025:1993**	$t \leq 40$		$40 < t \leq 150$
	S235JR / S235JRG1	0,35		–
	S235JRG2 t/m S235J2G4	0,35		0,38
	S275JR t/m S275J2G4	0,40		0,42
	S355JR t/m S355K2G4	0,45		0,47
	NEN-EN 10113-2:1993 [c]	$t \leq 63$		$63 < t \leq 100$
	S275N/NL	0,40		0,40
	S355N/NL	0,43		0,45
	S420N/NL	0,48		0,50
	S460N/NL	–		–
	NEN-EN 10113-3:1993	$t \leq 16$		$16 < t \leq 40$
	S275M/ML	0,34		0,34
	S355M/ML	0,39		0,39
	S420M/ML	0,43		0,45
	S460M/ML	0,45		0,46
2005-heden	**NEN-EN 10025-2:2004**	$t \leq 30$	$30 < t \leq 40$	$40 < t \leq 150$
	S235JR / S235J0 / S235J2	0,35	0,35	0,38
	S275JR / S275J0 / S275J2	0,40	0,40	0,42
	S355JR t/m S355K2	0,45	0,47	0,47
	S450J0	0,47	0,49	0,49
	NEN-EN 10025-3:2004	$t \leq 63$		$63 < t \leq 100$
	S275N/NL	0,40		0,40
	S355N/NL	0,43		0,45
	S420N/NL	0,48		0,50
	S460N/NL	0,53		0,54
	NEN-EN 10025-4:2004	$t \leq 16$		$16 < t \leq 40$
	S275M/ML	0,34		0,34
	S355M/ML	0,39		0,39
	S420M/ML	0,43		0,45
	S460M/ML	0,45		0,46

[a] Geldt voor alle dikten tot en met 100 mm, tenzij waarde gegeven voor $t \leq 35$.
[b] Bepaald met de maximumwaarden op basis van de chemische samenstelling van de ladinganalyse.
[c] Waarden van maximum-CEV gelden indien overeengekomen tijdens de bestelling.

(CEN-members, 2023)

G

Tolerances

Afmetingen en toleranties

F.1 Toleranties op de afmeting van de doorsnede

Het type staalprofiel en het profielnummer uit de profielserie moet worden bepaald door de afmeting van de profieldoorsnede (lengte, breedte, dikte flens, dikte lijf) op te meten en te toetsen aan de toleranties (zie tabel F.1).

Tabel F.1 — Normen voor dimensies en normen voor toleranties

Type profiel	Dimensies	Toleranties
I/H-profielen	NEN-EN 10365	NEN-EN 10034
L-profielen (gelijkzijdig/ongelijkzijdig)	NEN-EN 10056-1	NEN-EN 10056-2
I-profielen met tapsvormige flenzen	NEN-EN 10365	NEN-EN 10024
U-profielen	NEN-EN 10365	NEN-EN 10279
Platte staven	NEN-EN 10058	NEN-EN 10058
Vierkante staven	NEN-EN 10059	NEN-EN 10059
Ronde staven	NEN-EN 10060	NEN-EN 10060
T-profielen	NEN-EN 10055	NEN-EN 10055
Warmvervaardigde buisprofielen	NEN-EN 10210-2	NEN-EN 10210-2
Koudvervaardigde gelaste buisprofielen	NEN-EN 10219-2	NEN-EN 10219-2

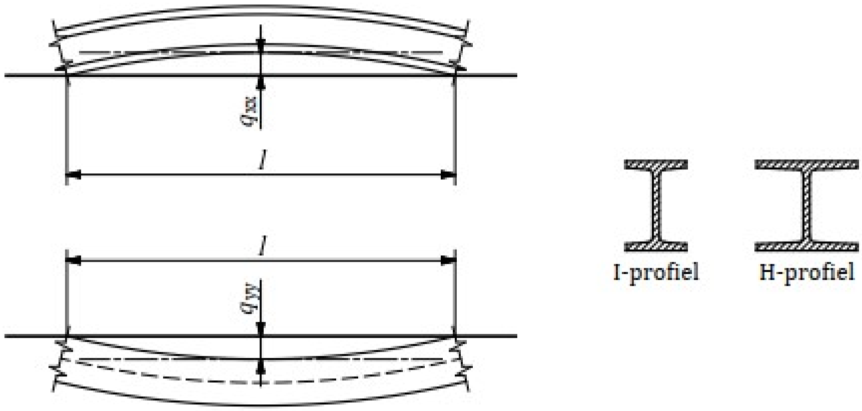
Als de afmetingen van de doorsnede voldoen aan de toleranties, dan mogen de doorsnede-eigenschappen (A, I en W) worden afgelezen uit de desbetreffende tabellen in de documentatie van de fabrikant, uit de app van Bouwen met Staal, of uit de relevante tabellen in dictaten en boeken.

Als de afmetingen van de doorsnede niet voldoen aan de toleranties, dan moeten de afmetingen volgens figuur 1.1 van NEN-EN 1993-1-1+C2+A1:2016 worden gespecificeerd en de doorsnede-eigenschappen worden bepaald met de mechanica.

F.2 Toleranties op de rechtheid van het staalprofiel

In alle gevallen zal moeten worden aangetoond dat het staalprofiel voldoet aan de toleranties op rechtheid door q_{xx} en q_{yy} te bepalen (zie figuur F.1 voor een voorbeeld met H- en I- profielen).

(CEN-members, 2023)



Legenda

l lengte

Figuur F.1 — Rechtheid van een staalprofiel (eigenschappen)

De afwijkingen q_{xx} en q_{yy} voor alle staalprofielen in de keuringseenheid mogen worden bepaald door uit de keuringseenheid de drie staalprofielen met de grootste afwijking te meten. Deze meetprocedure borgt dat γ_{M1} = 1,00 mag worden aangehouden als bij nieuw staal.

De afwijkingen q_{xx} en q_{yy} moeten worden bepaald in het horizontale vlak ten opzichte van een strak gespannen snoer dat dient als referentielijn volgens bijlage A van NEN-EN 10034:1994.

De afwijkingen q_{xx} en q_{yy} worden vervolgens getoetst aan tabel F.2.

Als de afwijking q_{xx} en/of q_{yy} niet aan de toleranties op rechtheid voldoet, dan mag deze worden gecorrigeerd door het staalprofiel te richten.

Tabel F.2 — Toleranties op rechtheid voor staalprofielen

Type profiel	**Norm**	**Profielhoogte *h*** mm	**Tolerantie op de rechtheid (q_{xx}/q_{yy}) over lengte *l***
I/H-profielen	NEN-EN 10034	$80 < h \leq 180$	0,3 % van l
		$180 < h \leq 360$	0,15 % van l
		$h > 360$	0,1 % van l
L-profielen (gelijkzijdig / ongelijkzijdig)	NEN-EN 10056-2	a ≤ 150 [a]	0,4 % van l
		150 < a ≤ 200	0,2 % van l
		a > 200	0,1 % van l
I-profielen met tapsvormige flenzen	NEN-EN 10024	$80 < h \leq 180$	0,3 % van l
		$180 < h \leq 360$	0,15 % van l
		$360 < h$	0,13 % van l

(CEN-members, 2023)

Type profiel	**Norm**	**Profielhoogte *h*** mm	**Tolerantie op de rechtheid (q_{xx}/q_{yy}) over lengte *l***
U-profielen	NEN-EN 10279	$h \leq 150$ $150 < h \leq 300$ $300 < h$ $h \leq 150$ $150 < h \leq 300$ $300 < h$	0,3 % van *l* [e] 0,2 % van *l* 0,25 % van *l* 0,5 % van *l* [f] 0,3 % van *l* 0,2 % van *l*
Platte staven	NEN-EN 10058	$b \leq 150$ [b] $b \times t < 1\,000$ mm² $b \times t > 1\,000$ mm² $b > 150$	Geen 0,4 % van *l* 0,25 % van *l* 0,4 % van *l*
Vierkante staven	NEN-EN 10059	a ≤ 25 [c] 25 < a ≤ 80 80 < a	Geen 0,4 % van *l* 0,25 % van *l*
Ronde staven	NEN-EN 10060	$d \leq 25$ [d] $25 < d \leq 80$ $80 < d \leq 250$	Geen 0,4 % van *l* 0,25 % van *l*
T-profielen	NEN-EN 10055	$50 \leq b, h \leq 100$	0,4 % van *l*
Warmvervaardigde buisprofielen	NEN-EN 10210-2	Rond Vierkant/rechthoekig Elliptisch	0,2 % van *l* en 3 mm over elke m 0,2 % van *l* en 3 mm over elke m 0,2 % van *l* en 3 mm over elke m
Koudvervaardigde gelaste buisprofielen	NEN-EN 10219-2	Rond Vierkant/rechthoekig Elliptisch	0,2 % van *l* en 3 mm over elke m 0,15 % van *l* en 3 mm over elke m 0,2 % van *l* en 3 mm over elke m

[a] a is de langste zijde van het L-profiel.
[b] *b* is de breedte en *t* is de dikte van de platte staaf.
[c] a is de zijde van de vierkante staaf.
[d] *d* is de diameter van de ronde staaf.
[e] Over de hoogte van het profiel (q_{xx}).
[f] Over de breedte van het profiel (q_{yy}).

(CEN-members, 2023)

H

Opening statement

You are being invited to participate in a research study titled ‘Achieving acceptance for the reuse of steel bridge components’. This study is being conducted by Marlien Schuurmans from the TU Delft in collaboration with Sweco Nederland.

The purpose of this interview is to gain insights into the perspectives of relevant stakeholders regarding the acceptance of steel reuse. The interview will take approximately 45 minutes to complete. The collected data will be used for a graduation thesis. You will be asked to share your general experience with reuse in the past, which obstacles you think are present and your perspective on the best ways to address these challenges.

As with any online activity the risk of a breach is always possible. Your answers in this study will remain confidential to the best of the ability. The data from the interview will be stored on a Sweco laptop and not transferred to another device. All data will be anonimysed in the thesis and recordings will be deleted after they are analysed.

Participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions if you prefer.

I

Informed consent form

Please tick the appropriate boxes.

Voluntary participation in research	Yes	No
1. I have read and understood the study information, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves audio-recording. The recording will be deleted after it is analysed.	☐	☐
Use of data for research		
4. I understand that taking part in the research also involves collecting personal information that can identify me, such as my name and/or email address, but will not be shared beyond this research.	☐	☐
5. I understand that the (identifiable) personal data I provide will be destroyed.	☐	☐
6. I understand that after the research study the de-identified information I provide will be used for the thesis report and presentation at Delft University of Technology.	☐	☐
7. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
Data storage		
8. I give permission for the de-identified data that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐

Name of participant: ____

Signature: ______________________________ Date: _____________________

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher: Marlien Schuurmans

Signature: Date: ____________________

J

Interview protocol

J.1. English

Introduction

1. Name of the researcher – Marlien Schuurmans
2. Field of study – MSc. Civil Engineering and Msc. Construction Management & Engineering
3. Research objective – Gaining insights from various perspectives into the obstacles to reusing steel, as well as determining the best strategy to remove these barriers to such an extent that what remains is 'acceptable'.
4. Signing informed consent form.

Opening questions

1. What is your role within your company, and what noteworthy experiences have you gained at other companies?
2. What is your experience with the reuse of materials in general?
3. " " steel in general?
4. " " steel bridge components?
5. What benefits are you aware of regarding the reuse of materials, or steel in particular?
6. What disadvantages " "?

Core questions
7. Despite the advantages, reuse is not yet the norm or standard. What do you see as obstacles to reuse?

I have identified five obstacles based on a literature research. I am curious about your perspective on each of them, so I will talk you through them.

- The first obstacle is finding and collecting reusable steel. This is challenging because the material properties of steel are sometimes uncertain as the documentation can be missing/lacking from the previous structure. When the properties are known or have been determined, a suitable location for application must be found. A component with certain properties may be suitable for one location but not another. Additionally, it must be available at the right place and time, meaning supply and demand need to be aligned.
  8. What is your view on this (are there additions, etc.)?

- A second obstacle is the lack of design standards. There are only NEN standards for designing with new materials, and the degradation of materials due to damage from the first life cannot currently be determined. As a result, it is not possible to design in a safe way, and creating NEN standards for reused materials is a time-consuming process, making this a significant issue.
  9. ” ”

- In addition to the lack of design standards, there is also a lack of regulations within the European Union. Products can be traded within the EU if they have a CE marking, but this is currently not possible for reused materials.
  10. ” ”

- The fourth obstacle is that the adoption of reused components is hindered by the need for the involvement of the entire construction ecosystem. Designers should be flexible in order to be able to design with a limited stock, clients must accept reused steel and the associated uncertainties, and users must have trust in order to use them.
  11. ” ”

- The fifth obstacle is that the costs of reuse may currently be higher than those of new production, and these costs are unevenly distributed across the construction industry. Costs are a key metric for companies and will certainly influence the success and feasibility of reuse practices.
  12. ” ”

13. What other obstacles could I add to complete the list?
14. What do you think is the most important obstacle to address and why?
15. How would reducing this obstacle influence other obstacles?

A lot of the obstacles are closely related to uncertainties (in technical knowledge, but also in costs and availability). It might be unfeasible to solve all the obstacles.

16. To what extent do you think the obstacles *should be* addressed? Or in other words: what uncertainties can to some extent not be *not* accepted?
17. What type of approach do you think is most suitable for dealing with these uncertainties and why? (integrated/holistic or step-by-step)?
18. Are there any other aspects you would like to add regarding strategies and/or obstacles?

Closing questions

19. If these strategies become adopted, how do you envision the future of reused materials?
20. Do you have anything to add?

J.2. Nederlands

Introductie

1. Naam van de onderzoeker – Marlien Schuurmans
2. Onderzoeksgebied – MSc. Civil Engineering en Msc. Construction Management & Engineering
3. Onderzoeksdoel – Inzichten verkrijgen van verschillende perspectieven over de obstakels in het hergebruiken van staal en wat de beste strategie is om deze struikelblokken dusdanig te kunnen verminderen dat wat overblijft acceptabel is.
4. Toestemmingsformulier ondertekenen.

Openingsvragen

1. Wat is jouw rol binnen je bedrijf en welke benoemenswaardige ervaringen heb je bij andere bedrijven opgedaan?
2. Welke ervaring heb je met hergebruik van materialen?
3. ” ” staal in het algemeen?
4. ” ” stalen brugcomponenten?
5. Welke voordelen ben je bekend mee rondom het hergebruiken van materialen of in het bijzonder staal?
6. Welke nadelen ” ”?

Kernvragen

7. Ondanks de voordelen is hergebruik nog niet de norm en standaard, wat zie jij als obstakels omtrent hergebruik?

Ik heb vijf obstakels geidentificeerd op basis van een literatuuronderzoek. Ik ben voor elk van deze benieuwd wat jouw visie hierop is.

- De eerste is het vinden/verzamelen van herbruikbaar staal. Dit is lastig omdat de materiaaleigenschappen van staal soms onzeker zijn, omdat documentatie van constructies vroeger kan missen of gebreken kan hebben. Wanneer de eigenschappen bekend zijn of zijn vastgesteld, moet een geschikte plek voor hergebruik worden gevonden. Een component met bepaalde eigenschappen kan geschikt zijn voor de ene locatie, maar niet voor de andere. Het moet bovendien op de juiste plaats en tijd beschikbaar zijn, wat betekent dat vraag en aanbod op elkaar afgestemd moeten zijn.
  8. Wat is je visie hierop (zijn er nog aanvullingen etc.)?

- Een tweede obstakel is het gebrek aan ontwerpnormen. Er zijn alleen NEN-normen voor het ontwerpen met nieuwe materialen, en de degradatie van materialen door schade uit het eerste leven kan momenteel niet worden vastgesteld. Hierdoor is het niet mogelijk om op een veilige manier te ontwerpen, tevens is het opstellen van NEN-normen voor hergebruikte materialen een tijdrovend proces, wat dit een significant probleem maakt.
  9. " "

- Naast het gebrek aan ontwerpnormen is er ook een gebrek aan regelgeving binnen de Europese Unie. Binnen de EU kunnen producten worden verhandeld als ze een CE-markering hebben, maar dit is momenteel niet mogelijk voor hergebruikte materialen.
  10. " "

- Het vierde obstakel is dat de adoptie van hergebruikte componenten wordt belemmerd door de noodzaak van betrokkenheid van het hele civiele ecosysteem. Constructeurs dienen flexibel te zijn om te ontwerpen met een beperkte beschikbaarheid aan profielen, klanten moeten hergebruikt staal en de bijbehorende onzekerheden accepteren, en gebruikers moeten ook vertrouwen hebben om ze te gebruiken.
  11. " "

- Het vijfde obstakel is dat de kosten voor hergebruik momenteel hoger kunnen zijn dan die voor nieuwe productie, en deze kosten zijn ongelijk verdeeld over het civiele ecosysteem. Kosten zijn maatgevend voor bedrijven en zullen zeker bijdragen aan het succes van de adoptie en acceptatie van hergebruikspraktijken.
  12. " "

13. Welke obstakels zou ik nog kunnen toevoegen om de lijst te completeren?
14. Welk obstakel denk jij dat het belangrijkst is om aan te pakken en waarom?
15. Hoe zou het verminderen van dit obstakel de andere obstakels beïnvloeden?

Veel van de obstakels zijn nauw verbonden aan onzekerheden (in technische kennis, maar ook in kosten en beschikbaarheid van profielen). Het is wellicht niet haalbaar om alle obstakels volledig op te lossen.

16. In hoeverre denk jij dat de obstakels *zouden moeten* worden aangepakt? Of met andere woorden: welke onzekerheden kunnen tot op zekere hoogte niet *niet* worden geaccepteerd?
17. Wat voor soort aanpak lijkt jou het meest geschikt om met deze onzekerheden om te gaan en waarom? (integraal of stukje voor stukje)?

18. Zijn er nog andere aspecten die je zou willen toevoegen omtrent strategieën en/of obstakels?

Afsluitende vragen

19. Als deze strategieën worden toegepast in de praktijk, hoe denk jij dat de toekomst van hergebruikte materialen eruitziet?
20. Als je nog iets wilt toevoegen, kun je dat nu laten weten.

K

Associated action points per stakeholder

This appendix presents an indicative overview of stakeholder roles, based on the earlier mapping between strategies and underlying obstacles in Section 12.1. The action points below are drawn from the interview data and the clustered analysis, and aim to clarify how different actors relate to enabling conditions for reuse.

- **Government:** Could take on a steering role by shaping the conditions under which reuse becomes more feasible,for example, by adjusting procurement requirements or introducing indirect incentives such as CO_2 legislation. In addition, the government might support front runners and monitor broader market participation through a ‘front runner–peloton’ approach
- **Front runners:** Are positioned to initiate pilot projects, generate practice-based knowledge, and explore solutions for remaining technical obstacles (e.g. safe removal of coatings). In some cases, front runners might also collaborate to develop missing technical specifications, such as design guidelines, testing procedures, or demolition criteria.
- **Peloton:** Refers to the larger group of market actors who currently participate less in reuse. These actors may gradually build confidence as reuse becomes more familiar, often through exposure to pilot projects or the sharing of practical knowledge.
- **Client:** Has the potential to influence demand by including reuse in tenders or project briefs. Clients may also support future reuse potential by improving asset management and data storage practices through BIM.
- **Demolition contractor:** Could help enable the supply of reusable materials by applying circular demolition methods.
- **Steel manufacturer:** May take on a role into the market by performing quality inspections, issuing certificates, and integrating reused steel with existing supply chains.
- **Chain-wide:** Collaborative efforts across the supply chain could support coordination, reduce uncertainty, and promote shared learning. Such partnerships may help close knowledge gaps and align expectations across different project contexts.