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Abstract

This thesis presents the theoretical foundation for reusing steel from decommissioned offshore structures in onshore construction projects as a green alternative to new production steel. This would open up a new source of materials in the supply chain of steel components, and contribute to a reduction in the demand of new production steel. Although the conditions and circumstances are different, reuse of offshore steel carry many similarities with onshore steel reuse. This thesis utilizes and modifies already existing guidelines for onshore reuse to determine the feasibility. Included in the feasibility study is one of the most deciding factors of the offshore reuse method, which is the quality check. The thesis proposes a quality check procedure which is based on current guidelines for standards on inspection, testing, and technical delivery conditions.

The theory presented in this thesis is put to the test in a case study, where the result indicate that despite significant environmental benefits, reused offshore steel is not yet a viable option in procurement of materials in the onshore construction industry. The feasibility study reveals a reusability index of 51,5%, which is lower than what would constitute a viable reuse operation. However, the reusability index is predicted to increase if the reuse operation is centralized and streamlined by the decommissioning companies.

Keywords: Steel reuse, offshore structures, sustainability, LCA

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List of Notations

BOF	Basic oxygen furnace
C/S	Cross-section
CBS	Cost breakdown structure
CF	Corrosion fatigue
DT	Destructive testing
EAF	Electric arc furnace
EPD	Environmental product declaration
FEM	Finite element method
GWP	Global warming potential
HCF	High cycle fatigue
LCA	Life cycle analysis
LCC	Life cycle cost
LCF	Low cycle fatigue
NDT	Non-destructive testing
RP	Recommended practice
ULCF	Ultra low cycle fatigue
ULS	Ultimate limit state

α	Model parameter for pitting corrosion
β	Model parameter for pitting corrosion
σ_u	Ultimate strength
σ_y	Yield strength
$\sigma_{fatigue}$	Lower fatigue stress limit
σ_{HCF}	High cycle fatigue stress range
σ_{LCF}	Low cycle fatigue stress range
σ_{ULCF}	Ultra low cycle fatigue stress range
A	Model parameter for uniform corrosion
B	Model parameter for uniform corrosion
C_{new}	Cost of new steel element
C_{reuse}	Cost of reused steel element
D_d	Accumulated fatigue damage
m	Mass
P	Cost savings connected to reused elements
R	Reusability index for an entire structure
r	Reusability index for single element
w	Weighting factor

Preface

This thesis is written and submitted as the final work requirement for completion of a masters degree in civil engineering at the University of Stavanger.

The subject of the thesis was recommended to me by the Prof. Sudath C. Siriwardane at the faculty of Science and Technology Department of Mechanical and Structural Engineering and Materials Science at UiS. The thesis has been written in cooperation with the Sweco Porsgrunn office. Here I have been provided with an office, a supervisor, a project for a case study.

I would like to express my gratitude to Sudath C. Siriwardane and Fredrik Bjørheim for excellent supervision and continuous support throughout the semester of the thesis work. I would also like to thank my co-supervisor at Sweco, Sigmund Røland, and the rest of the Sweco Porsgrunn office for the opportunity to write my thesis with them in a professional work environment.

Chapter 1

Introduction

1.1 General

As the world is facing climate crisis, all parts of society have an obligation to do whatever possible to reduce the carbon footprint, the construction industry is no exception. There are countless measures to be taken within the construction industry, in particular within production of building materials. The steel production industry alone releases 3-billion-ton CO_2 each year [1], which corresponds to approximately 8% of all man-made CO_2 emission worldwide. This includes the recycling and remelting of steel, which is an extremely energy consuming and environmental harmful process, as the energy mostly comes from fossil fuels. For decades scientists and engineers have entertained the idea of decarbonizing steel production by replacing energy from fossil fuels with renewable electricity through the HYBRIT process (The hydrogen breakthrough ironmaking technology), which utilizes hydrogen produced created with renewable energy sources [1]. However, this method is not yet fully developed and operational, and expected to increase production cost, so the steel industry must look at other alternatives.

Another way to reduce the carbon footprint in the steel industry is to reuse steel. This means altering the standard life cycle of steel in a way that is beneficial both environmentally and economically. As displayed in Figure 1.1, the life cycle of steel can be divided into five main phases.

- **Raw materials** - Mining and extraction of raw materials used in steel production
- **Steel production** - Production of relevant steel alloys from raw materials
- **Manufacturing** - Processing steel from production steel to working steel components
- **Service life** - Manufactured steel components serving its intended purpose
- **Recycling** - End of life material collection, sorting, scrapping and remelting

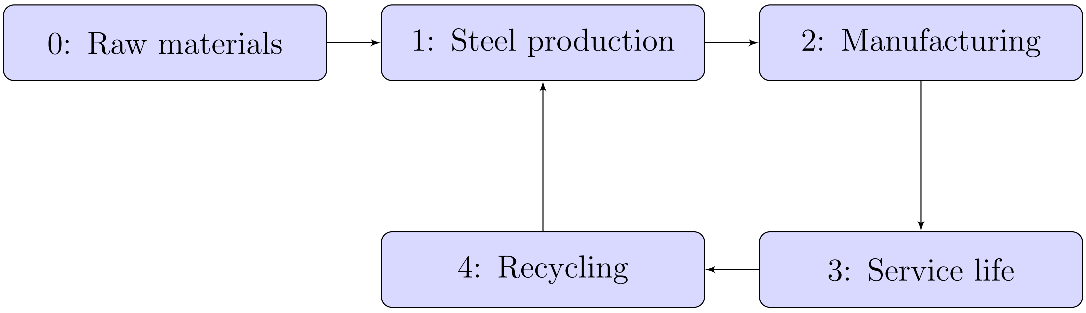


Figure 1.1: Full circle life cycle of steel

Among these five phases of the life cycle, phases 0: raw material, 1: steel production and 4: recycling are the most energy demanding and environmental harmful phases. The method of reusing steel offers the chance to bypass these phases all together and skip directly to the manufacturing phase. Under some circumstances, even the manufacturing phase is redundant, as the steel components satisfies the requirements of the new project as is with no need to be additionally processed before being reintroduced into another service life.

When considering reusage of steel in a construction project, material supply could be a problem. There are methods developed to utilize reusable steel from decommissioned onshore structures, however, there is another source of supply, namely the offshore industry. There are 2000 offshore oil- and gas platforms in the world scheduled for decommissioning by year 2040 [2]. With platforms weighing up to 30 000 metric tons [3], this could serve as a big source of supply if utilized correctly. Procurement of steel from decommissioned offshore installations has the potential to provide a greener alternative for both the donor platform, as well as the structure in which the steel members are being used.

Along with the potential environmental benefits that comes with reusing steel from the offshore industry, is also an economic aspect. How would the different phases of construction projects (such as procurement, handling, and construction) change from an economic perspective when utilizing pre-used steel in the construction industry? This is a highly relevant question for economically invested stakeholders in a construction project to ask, and a complex question to answer, considering all the different parties which are involved in each phase of the process. Companies are unlikely to make environmentally beneficial changes to their operation without economical incentives, or that the changes made are cost-wise indifferent.

Reuse of steel from onshore structures is a tried and tested method. However, this method considers to a large extent reuse on a structural level, i.e. relocation of entire buildings [4]. Reuse of steel on component level would require total repurposing of steel elements, which is the case for this study of decommissioned offshore installations. This requires a different approach on feasibility studies, which includes comprehensive degradation analysis, strength calculations and re-designing procedures.

1.2 Scope and objectives

The objective of this thesis is to investigate the possibilities of using reclaimed steel elements from decommissioned offshore installations instead of new production steel. In addition to the feasibility study, the thesis will also cover the environmental-, and the economical aspect of reusing steel from the offshore industry. This includes a background study of the decommissioning process and availability check. The focus area is utilizing current guidelines for reusability of onshore structures as well as relevant design- and quality standards to develop a method of reusing structural steel components from the offshore industry in the onshore construction industry. The thesis will only focus on design of new structures with reclaimed steel, not on designing structures for the purpose of being reused.

While there are applications for reclaimed steel from decommissioned ships and dock facilities, this thesis will only concern itself with load carrying steel components from the topside of decommissioned offshore oil- and gas rigs. The thesis will also contain a case study where the information gathered, and research conducted will be utilized in a real-life situation. The case study, which is provided by the Sweco Porsgrunn office, is an apartment building made of steel and concrete. The task is to investigate whether the designed steel components could have been replaced by reclaimed structural steel components from decommissioned offshore platforms.

1.3 Content

The thesis is divided into six chapters. Following is an overview of organization and content of this thesis' chapters.

- **Chapter 1 - Introduction:** Briefly presents the background and scope of the thesis.
- **Chapter 2 - Theories and state of the art:** Presents currently used reuse analysis methods and guidelines, as well as standards relevant to the reuse procedure. It also presents common degradation mechanisms, and environmental and economic consequences of steel reuse.
- **Chapter 3 - Reuse methodology:** Goes into specifics of the approach of steel reuse from offshore structures. This includes an overview of the entire reuse process, inspection/testing procedures, and adaptation of onshore reuse analysis methods to be suitable for offshore structures.
- **Chapter 4 - Case study:** This chapter combines the content of chapters 2 and 3 with a real-life project to assess the feasibility and viability of offshore reuse. It also identifies the issues and challenges regarding reuse from offshore structures.
- **Chapter 5 - Results and discussion:** Presents the results of the case study, discusses specific problems that needs to be addressed, and proposes solutions to these problems.
- **Chapter 6 - Conclusions:** Summarizes the thesis, and presents a conclusion based on the previous chapters. This chapter also presents suggestions for further work that would increase the viability of reused steel in the construction industry.

Chapter 2

Theories and state of the art

2.1 Guidelines for steel reuse

2.1.1 Quality assessment

When designing onshore steel structures, there are rules and regulations that must be adhered to in the form of Eurocode 3. This code addresses all aspects in design of new steel structures, including documents covering relevant load cases, geometry, and material properties. The code assumes the steel being used in the design satisfies the quality requirements of EN 10025-1 [5], which specifies the delivery conditions for hot rolled structural steel, i.e. the European standard of steel quality. Eurocode 3 applies also when utilizing reclaimed steel in the design process, which in turn means that the reclaimed steel needs to have the same quality as new production steel.

In a decommissioning process there are two scenarios in which to ensure the quality of the steel is sufficient for reuse:

- **Scenario 1** - Steel members meet performance requirements, and comes with original quality certification.
- **Scenario 2** - Steel members are re-certified through comprehensive material testing.

These two scenarios will be explained further in Chapter 3.1.2

2.1.2 Standards and guidelines

When developing a recommended practice (RP) for reuse it is vital to have a standardized set of acknowledged guidelines to follow. As of today, there is no internationally recognized standard for steel reuse, only RPs. These RPs consider reuse from onshore structures, and are based on existing documents regarding product standards, delivery conditions, testing procedures etc. The quality of the pre-used steel from offshore structures must be verified through the same channels as any other pre-used steel. Relevant standards and guidelines regarding structural steel are listed below.

Design guidelines

- **EN 1993 (EC3):** Design of steel structures using limit state design

Guidelines for quality requirements

- **EN 1090-1:** Requirements for conformity assessment for structural components (CE-marking) [6]
- **EN 1090-2:** Technical requirements for the execution of steel structures [7]
- **EN 10025-1:** General technical delivery conditions of structural steels [5]
- **EN 10025-2:** Technical delivery conditions for non-alloy structural steels [8]
- **EN 10346:** Continuously hot-dip coated steel flat products for cold forming - Technical delivery conditions [9]

Guidelines for inspection/testing

- **EN 13018:** Non-destructive testing – Visual testing – General principles [10]
- **EN ISO 6892-1:** Metallic materials — Tensile testing — Part 1: Method of test at room temperature [11]
- **EN ISO 14284:** Sampling and preparation of samples for the determination of chemical composition [12]
- **EN ISO 148-1:** Metallic materials - Charpy pendulum impact test - Part 1: Test method [13]
- **ISO 6507-1:** Metallic materials — Vickers hardness test — Part 1: Test method [14]
- **ISO 6508-1:** Metallic materials — Rockwell hardness test — Part 1: Test method [15]
- **EN ISO 13385-1:** Geometrical product specifications (GPS) - Dimensional measuring equipment - Part 1: Design and metrological characteristics of callipers [16]
- **EN ISO 13385-2:** Geometrical product specifications (GPS) — Dimensional measuring equipment — Part 2: Design and metrological characteristics of calliper depth gauges [17]
- **ISO 14577-5:** Metallic materials — Instrumented indentation test for hardness and materials parameters — Part 5: Linear elastic dynamic instrumented indentation testing (DIIT) [18]
- **ISO 19272:** Low alloyed steel — Determination of C, Si, Mn, P, S, Cr, Ni, Al, Ti and Cu - Glow discharge optical emission spectrometry (routine method) [19]
- **ASTM E 572:** Standard Test Method for Analysis of Stainless and Alloy Steels by Wavelength Dispersive X-Ray Fluorescence Spectrometry [20]

- **ASTM 1476:** Standard Guide for Metals Identification, Grade Verification, and Sorting [21]
- **ASTM E 112:** Standard Test Methods for Determining Average Grain Size [22]

2.2 Reusability assessment

One of the main challenges with reusage of steel structural members/steel components/steel structures, is defining a method to assess the reusability. While there is currently no acknowledged method or procedure to do this, there is a proposed approach to this problem developed by Technical Research Center of Finland Ltd. [23]. The method is called reusability index, and it involves assessing and quantifying different individual performance categories of the reusing process based on feasibility. The reusability index is a helpful tool in determining the difficulty regarding reusability in a particular decommission project. Chapter 2.2 will go into deeper explanation as to what this method is, and how it works.

2.2.1 Reusability index

The method divides the decommissioning process into eight categories consisting of separate work packages, and grades them in order of feasibility. The different categories are listed below:

- **Deconstruction** - How complicated is the deconstruction process in a particular decommissioning project. This category considers how the structure is assembled (bolted, welded, riveted, etc.), how accessible the members are, and how easily the deconstructed members are extracted from the structure.
- **Separation and cleaning** - This category assess the process of cleaning the different members after dismantling. It also takes into account if the steel members are extracted in bulks and need additional work after deconstruction.

It is likely that the members need new surface treatment, which falls under this category.

- **Handling and manipulation** - This category considers the difficulties with handling and manipulation on the site. The deconstructed structure also need to be transported to a storage facility where it will be stored until its transported to the building site in which it will be reused, or directly to the new site.
- **Quality check** - The quality of the steel members needs to be verified. The easiest way to do this is to check with the original design documentation if it is available, if not, the quality must be verified to satisfy the requirements of a series of standards and quality guidelines.
- **Geometry check** - Verification of all relevant dimensions and tolerances, ensuring there is no damage such as yielding or buckling that will affect the structural integrity of the new structure.
- **Redesigning** - The process of redesigning the steel member to serve its purpose in the new structure. For steel members this mostly involves shortening of beams/columns and/or change the fastening method to increase suitability in the new structure.
- **Repurposing** - To what extent is it possible to repurpose the member to its new intended use. For instance, a column may be repurposed as a beam, dependent on what is needed, and what is available.
- **Modification** - Modify either the steel member to fit the planned structure, or modify the planned structure to comply with the available reused steel member.

The feasibility in the different performance categories is graded from 0 (Impossible) to 1 (very easy). The reusability of a single structural member is defined as:

$$r = \Sigma \rho_i w_i \tag{2.1}$$

where ρ_i is the result of the assessment in the individual performance category, and w_i is the weighting factors of the individual performance categories. The weighting factors are added to obtain a reusability index r between 0 and 1. This is further explained in Chapter 3.2.2. To perform a reusability assessment for an entire structure, the accumulated result R is calculated with Equation 2.2.

$$R = \frac{\Sigma r_i m_i}{\Sigma m_i} \tag{2.2}$$

where r_i and m_i are the reusability and mass of the individual structural members respectively. Table 2.1 shows a detailed overview of the conditions used to assess the different performance categories.

Table 2.1: Performance categories. Table extracted from [23] and modified by author with permission from John Wiley & Sons.

Category	ρ_i = **20%**	ρ_i = **40%**	ρ_i = **60%**	ρ_i = **80%**	ρ_i = **100%**
Deconstruction	Welded connections, high risk of damage during deconstruction	Welded connections between components with difficult access	Mostly welded connections between components	Bolted connections between components with difficult access	Easily accessible bolted connections between components
Handling and manipulation	Exceeding standard transport dimensions, prone to damage, requires special protection	Standard transport, prone to damage, requires special protection	Manipulation by crane, not damage sensitive	Small lifting devices	Manipulation by hand
Separation and cleaning	Machine cleaning/cutting needed to separate other materials	Hand tools for cleaning/cutting can be used to separate other materials	Bolted connections with difficult access for separation	Bolted connections need to be removed for separation	Free-standing components requiring no cleaning
Redesigning	No documentation, components would not fulfil the standard design requirements without modification	No documentation available, new design is required	Design documentation available	Detailed documentation available incl. loading and maintenance history	Designed to be reused, documentation and maintenance records in digital format
Repurposing	Unique sizes and shapes, no other application possible	Possible to reuse for another purpose with some remanufacturing	Limited possibility to use for another purpose	Possible to use for another purpose even outside the construction sector	There is a larger demand for another application than the original purpose
Modification	Sizes are unique, reuse would require complete remanufacturing	Requires removal of welded parts	Requires addition and adjustment of bolt-holes	Requires only addition of new components	Requires no modification
Quality check	No documentation, demanding environment, loading history is difficult to estimate, laboratory tests are needed	Laboratory tests are needed to check material properties	Documentation available, loading history known, on-site test needed to check material properties	Material documentation available incl. loading and maintenance history	Material documentation available. Exploited in less demanding environment
Geometry check	Components would not pass geometry requirements without modification	Complex geometry 3D scanning required	Need to confirm positions of bolt-holes, etc.	Straightness and distortion check needed (lasers)	Straightness enough to confirm usability (wire, visual, etc.)

2.3 Damage assessment

When discussing reusing steel from offshore installations, one could argue that original quality certification alone would be insufficient documentation. Most offshore oil rigs in the North Sea are designed for a service life of 20-25 years, although in some cases this life expectancy is increased due to life extending measures taken during its service life. It is also possible that on inspection, the structure is found to be in better condition than originally expected, and therefore is deemed fit for service for an extended period of time.

During their service life, offshore structures are subjected to degradation mechanisms such as harsh corrosive environments and fatigue loading. If steel components from these structures were to be reused in land-based structures, it is vital to assess and quantify the accumulated damage from these degradation mechanisms before using them in the design.

2.3.1 Corrosion

Electrochemical oxidation, more commonly known as corrosion is a time-based degradation mechanism. Corrosion occurs when metals react with oxides (chemical compounds containing oxygen), causing a degradation in strength, appearance, and permeability. Due to the harsh offshore environment, corrosion remains one of the most challenging problems in the offshore construction industry. As well as being harmful in itself, corrosion has an accelerating effect on other degradation mechanisms. There are two main types of corrosion:

- **Uniform corrosion -** An evenly distributed layer of corrosive material is formed along the surface of a plated structure, leading to a reduced cross-sectional area. The reduction of cross-sectional area will affect the geometrical properties of the member, causing reduced axial-, shear-, moment- and torsional capacity. In most cases the loss of material on the steel member will lead to a shift in the geometrical neutral axis, causing eccentricity and added bending moment.

- **Pitting corrosion -** Localized penetrating occurrence of corrosion, causing stress redistribution in the member. This is the more severe type of the two corrosion types and is often found on members subjected to especially harsh environments, such as the splash zone on a jacket structure.

When discussing reuse of structural steel from offshore installations, it is best to avoid elements that shows signs of severe corrosion damage, i.e, large accumulation of pitting corrosion.

Calculation of corrosion depth

If the condition of the reusable steel member is unknown or if it for any reason is not possible to do an inspection, it is possible to make educated guesses with regards to corrosion. For uniform corrosion accumulation the depth of the degraded material can be described with a non-linear function. The reason behind the non-linearity is that the corrosive layer functions as a retarder for further corrosion development, causing the corrosion rate to decrease. Function for uniform corrosion is described in Equation 2.3 [24].

$$W(t) = A(t - t_{pt})^B \tag{2.3}$$

$W(t)$ is the corrosion depth in millimeters, t is age of structure in years and t_{pt} is the age of structure when sign of uniform corrosion first was discovered (pt = protection time). A and B is input parameters determined by steel type and environment.

Similarly, the function for pitting corrosion depth is described in Equation 2.4 [24].

$$W(t) = \alpha(t - t_i)^\beta \tag{2.4}$$

$W(t)$ is pit depth, t_i is time of pit instigation, and t is age of structure. α and β is input parameters determined by steel type and environment. According to [24], in a marine environment such as an offshore oil platform, the time period up to pit instigation t_i is negligible compared to t at the end of the structures life cycle, and can often be set equal to 0. Although pitting corroded members should be avoided in a reuse scenario, it is possible to reuse members which have been subjected to uniform corrosion. This is due to the more predictable nature of the uniform corrosion model.

Table 2.2: Model parameters for uniform corrosion development in offshore environments. Table extracted from [24] with permission from Elsevier.

	Splash zone area		**Other areas**	
Inspection findings	A(mm)	B	$A(mm)$	B
Not performed - unmanned facility or high costs involved	0,3	1	0,1	1
Severe corrosion found - uniform corrosion with many patches and pitting corrosion	0,3	0,823	0,1	0,823
No significant corrosion - slight uniform corrosion with few patches	0,252	0,823	0,084	0,823

2.3.2 Fatigue

Fatigue is one of the primary reasons for failure in offshore steel structures. It is defined as damage due to repetitive load cycles that generates stresses below a certain limit. With regards to stress ranges, there are three types of fatigue:

- **High cycle fatigue (HCF)** - Stresses ranges in the elastic limit:

$$\sigma_{fatigue} < \sigma_{HCF} < \sigma_y$$

- **Low cycle fatigue (LCF)** - Stresses ranges in the plastic limit:

$$\sigma_y < \sigma_{LCF}$$

- **Ultra low cycle fatigue (ULCF)** - Stresses are just below the ultimate limit (less than 20 load cycles before failure):

$$\sigma_{ULCF} \simeq \sigma_u$$

When assessing fatigue damage with the purpose of reusing steel members, it is not recommended to utilize components that have been subjected to LCF and ULCF, as these members most likely have suffered from some form of permanent deformation. However, when discussing reusing steel from the offshore industry, this aspect is probably not relevant as the structures have been operational for many years, which means LCF is the relevant fatigue mechanism. In any case, it is important to know the loading history of the steel to 1) determine whether to proceed with the reusability assessment of the particular member (or group of members), and 2) in the assessment itself.

For fatigue life calculations of onshore structures, the relevant guideline is EN 1993-1-9 from Eurocode 3. This guideline provides methods for fatigue resistance assessment based on statistics from comprehensive testing of specimens, including imperfections in materials and execution. Test results form a basis for S-N curves that describe the relationship between stress and number of cycles before failure in a steel detail. EN 1993-1-9 is limited to structures operating under normal atmospheric conditions and does not cover the effect of seawater corrosion [25]; hence it is not applicable when assessing offshore structures. Det Norske Veritas (DNV) have developed a recommended practice (RP) [26] for fatigue assessment of offshore structures that is based on the same principals as EN 1993-1-9. The S-N curves in this RP are tailored marine conditions and takes into account the effect of degradation mechanisms which are relevant to this environment, such as corrosion fatigue.

Fatigue loads on offshore installations are to a large extent due to wave- and wind loads. These loads result in horizontal and/or vertical acceleration in the structure which when multiplied with the mass, gives a cyclic load in addition to the residual static loads. In order to accurately quantify the resulting stresses from these loads in a particular steel member, FEM analysis software would have to be utilized. The input parameters in the FEM analysis are significant wave height H_S and the wave period T_Z. These parameters can be obtained from scatter diagrams in the DNV RP-C205 [27]. This constitutes a basis for a service life simulation of the structure, which would provide a stress history of any part of the structure. The next step would be to use Miner's rule [28] to calculate the accumulated damage due to fatigue.

Equation 2.5 displays Miner's rule:

$$D_d = \sum_{i}^{n} \frac{n_{Ei}}{N_{Ri}} \tag{2.5}$$

Where

- D_d is the accumulated damage due to cyclic loading

- n_{Ei} is the number of cycles the member is subjected to in a particular stress range

- N_{Ri} is the number of cycles until failure in the corresponding stress range

The result of this kind of analysis would paint a picture of the condition of the steel member considered for reuse and form a basis for re-certification. However, when discussing reuse of steel from the topside of an offshore oil rig in onshore structures, it is generally the beams and columns within certain measurements which are of interest. The hotspot stresses mostly occur in the welded connections, bolts, and joint details in general. Hence, it is these locations which are mostly subjected to fatigue failure, not the steel elements. This is reflected in the detail categories in the recommended practice from DNV. Non-welded details (i.e., beams and columns which are subjected to bending and axial load respectively) belongs in detail category B, which corresponds with the upper S-N curves depicted in Figure 2.1. Similarly, welded details have less fatigue resistance, and belong in detail categories corresponding to S-N curves lower on the diagram.

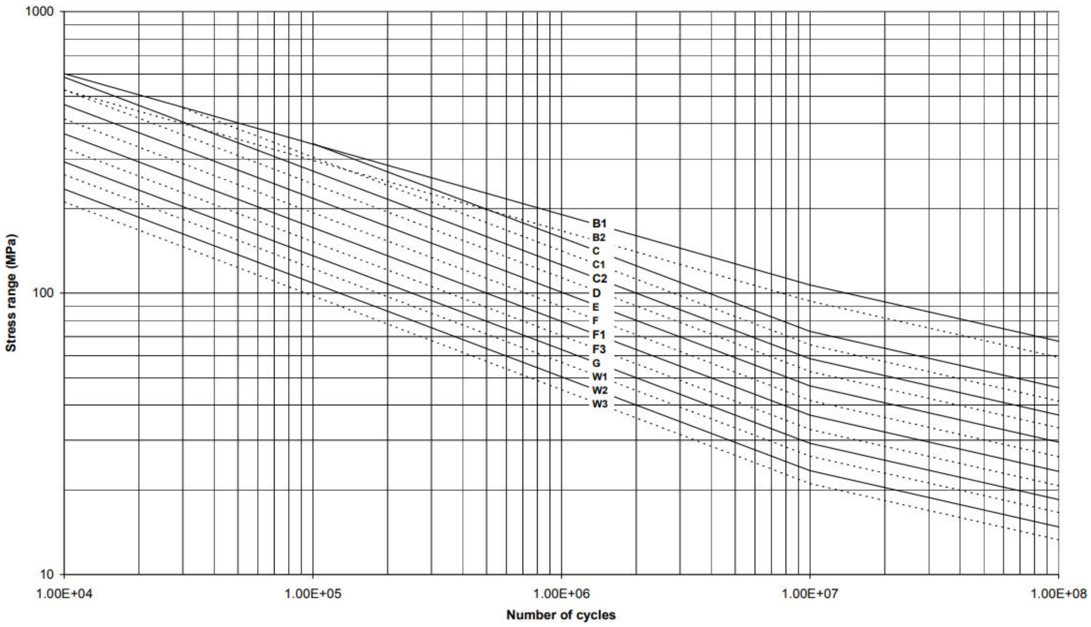


Figure 2.1: S-N curves in free air from DNV-RP-C203 [26]

Figure 2.1 is taken from DNVs recommended practice for fatigue design of offshore steel structures [26]. The y-axis represents stress range, and the x-axis represents number of load cycles. The diagram shows that the same stress range denotes different fatigue lives for different detail categories.

2.4 Economic benefits of reuse

Cost is a strong deciding factor of any construction project. Clients wants to pay as little as possible for their building, and contractors wants to maximize their profits. Among the expenses in a construction project is acquisition of building materials. Firstly, in order to analyse the procurement cost in a project with respect to new vs. reused steel, the cost breakdown structure must be defined. The University of Cambridge published an article with a proposed model of the costs connected to reused steel vs. new steel [29]. The model is based on extensive research within the construction industry in the UK, with interviews of several key players which have to do with decommissioning, procurement, and construction. The model breaks down the total cost of structural steel (reusable and new) into separate work package expenditures including everything ranging from procurement to assembly. Costs related to different operations are listed below.

Costs exclusively related to reused steel:

- **O** - Cost of reusable steel from stockist
- **D** - Deconstruction costs
- **R** - Fabrication costs for reusable steel (reconditioning)
- **T** - Transport and handling costs of reusable steel

Costs exclusively related to new steel:

- **N** - Cost of new steel from wholesaler/retailer
- **t** - Transport costs of new steel

Cost related to both reused and new steel:

- **F** - General fabrication costs (administration, design, coating, assembly etc.)

D is the disassembly cost, while R is the cost of refurbishing the steel to reusable standard, i.e. weld removal, sandblasting etc. N is price of new steel elements, and O is the reduced price for the pre-used elements. Additional transport and handling costs for pre-used steel elements T must be expected, as the supply of pre-used steel most likely does not meet the steel demand in the industry. The probability for the right type, and quantity of steel elements being available to meet the demands geographically and timing-wise is very low. t is therefore defined as transport and handling cost of new steel, due to a more streamlined operation. F is the general fabrication costs, which include costs of administration services, design work, coating, and erection of elements on the building site [29]. Costs in the F category are costs that would occur regardless of the state the steel elements are in, and would therefore not affect the results of the new vs pre-used cost assessment, as presented in Equation 2.8.

The cost of a reused element C_{reuse} is defined as:

$$C_{reuse} = O + D + R + T + F \tag{2.6}$$

The cost of a new element C_{new} is defined as:

$$C_{new} = N + t + F \tag{2.7}$$

Subtracting Equation 2.6 from Equation 2.7 will provide the expected savings P when opting for reused elements. If this number is negative it is economically advantageous to choose new elements over reused ones [29].

$$P = N + t - O - D - R - T < 0 \tag{2.8}$$

2.5 Environmental benefits of reuse

The steel production industry is among the world leading greenhouse gas emitters. Although data and statistics vary, it is generally recognized that the production of steel accounts for about 8% [30] of all the CO_2 emission on a global basis. The measures taken to reduce this number generally revolves around decarbonizing the industry by replacing the conventional basic oxygen furnace (BOF) method with electric arc furnace (EAF), and hydrogen-based steel production. The main downsides of this change in technology is green energy supply related to EAC, and the increased cost related to the hydrogen-based alternative.

As of today, every ton steel produced is emitting on average 1.85 ton of CO_2 globally [31]. By utilizing the reuse strategy, the environmental impact can be reduced by 97% compared to new production steel [32]. In theory, if it proves possible to erect a building exclusively using pre-used steel elements, it could save close to 1.85 ton of CO_2 per ton steel used. However, this hypothesis comes with some reservations. Environmental benefits related to reusing steel mainly stems from the absence of production processes, but there are other sources of pollution related to the reusing process.

- **Additional transport emissions** - As with the cost aspect of reuse, additional emissions related to transport of pre-used steel elements must be considered. When building with new production steel, the infrastructure for a streamlined operation is normally in place before construction start. This is not a matter of course if contractor opts for pre-used steel.
- **Emissions related to fabrication** - Some additional emissions related to disassembly and reconditioning of the pre-used steel must be considered, but this can prove difficult to quantify and calculate. This includes the use of chemicals, and energy consumed in the remanufacturing process.

To get a complete overview of the environmental impact the reuse method has on the construction project, a life cycle analysis (LCA) must be carried out. This kind of analysis provides detailed mapping on all kinds of environmental harmful emissions in every part of the members' life cycle. It is preferably be done in suitable software, with input parameters based on statistical data regarding steel production, transport, waste processing and remanufacturing.

2.6 Alternative applications for decommissioned offshore installations

2.6.1 Disposal and recycling

When an offshore installation reaches the end of its service life, it needs do be disposed of in a safe and environmentally friendly manner. Today there are several approaches to the dispose of offshore infrastructure. The topside of the rig can be dismantled in situ or transported to a dismantle yard. The most common way is to transport the platform to a shipyard before dismantling. With this approach, the rig is either dismantled into modules in the reversed order in which it was assembled, or the whole structure is transported using purpose built ships [33]. In each case engineers perform tests, calculate and check whether the structure can withstand the new load patterns due to transportation. The jacket structure is transported separately. Once arrived in the disposal facility, it is further dismantled and then recycled.

2.6.2 Relocation

In certain situations it may be sensible to relocate the entire platform, for instance if an oil well runs dry before the end of the platforms service life. It will then have to pass an inspection from relevant authorities to be declared fit for further production. Under these circumstances, the platform may be relocated to a new site where it can continue to serve its purpose as an oil rig.

2.6.3 Other applications

There are alternatives to recycling, if after inspection the decommissioned structure is considered to be outside of the serviceability requirements. Marine biologists have discovered that the steel jacket structures from offshore installations serves as an ideal skeleton for coral reefs. This provides a basis of life for a large diversity of species beneath the ocean surface. For some species, the ecosystems occurring along the jacket structures provides an even better nursery than that of a natural reef [34]. This application only requires the jacket structure, i.e., the top side of the platform needs to be removed as described in Chapter 2.6.1. However, there are examples where the entire platform has been appointed a new use. There have been examples of oil rigs that has been converted into diving resorts, in which one of the attractions is the coral reef on the jacket structure [35]. There is also talk of turning abandoned oil rigs into eco-friendly luxury hotels [36].

Chapter 3

Reuse methodology

3.1 Reuse procedure

3.1.1 General

In order to streamline and industrialize the supply of reused offshore steel in the onshore construction industry, there needs to be in place a generally acknowledged practice on how to assess and approach the reuse process. This practice would have to include everything from pre-decommissioning assessment of the donor platform to delivery on new construction site, based on a detailed assessment of reusability. The reusability assessment would be divided into three main parts. Firstly, a feasibility study to investigate whether it is reasonable to implement a reuse scenario in the construction process. This study is the main bulk of the assessment, as the reuse strategy must be reasonably feasible to carry out. The two remaining aspects are cost and environmental considerations, which are somewhat connected to each other. Cost analysis to examine whether reuse is economically viable over new production steel, and analysis of the environmental aspect to investigate the benefits of reuse over new production steel. Stakeholders and contractors are generally interested in environmentally friendly solutions, but not at the cost of project costs and profits respectively. Figure 3.1 shows a flowchart of a proposed reusing process of offshore structures.

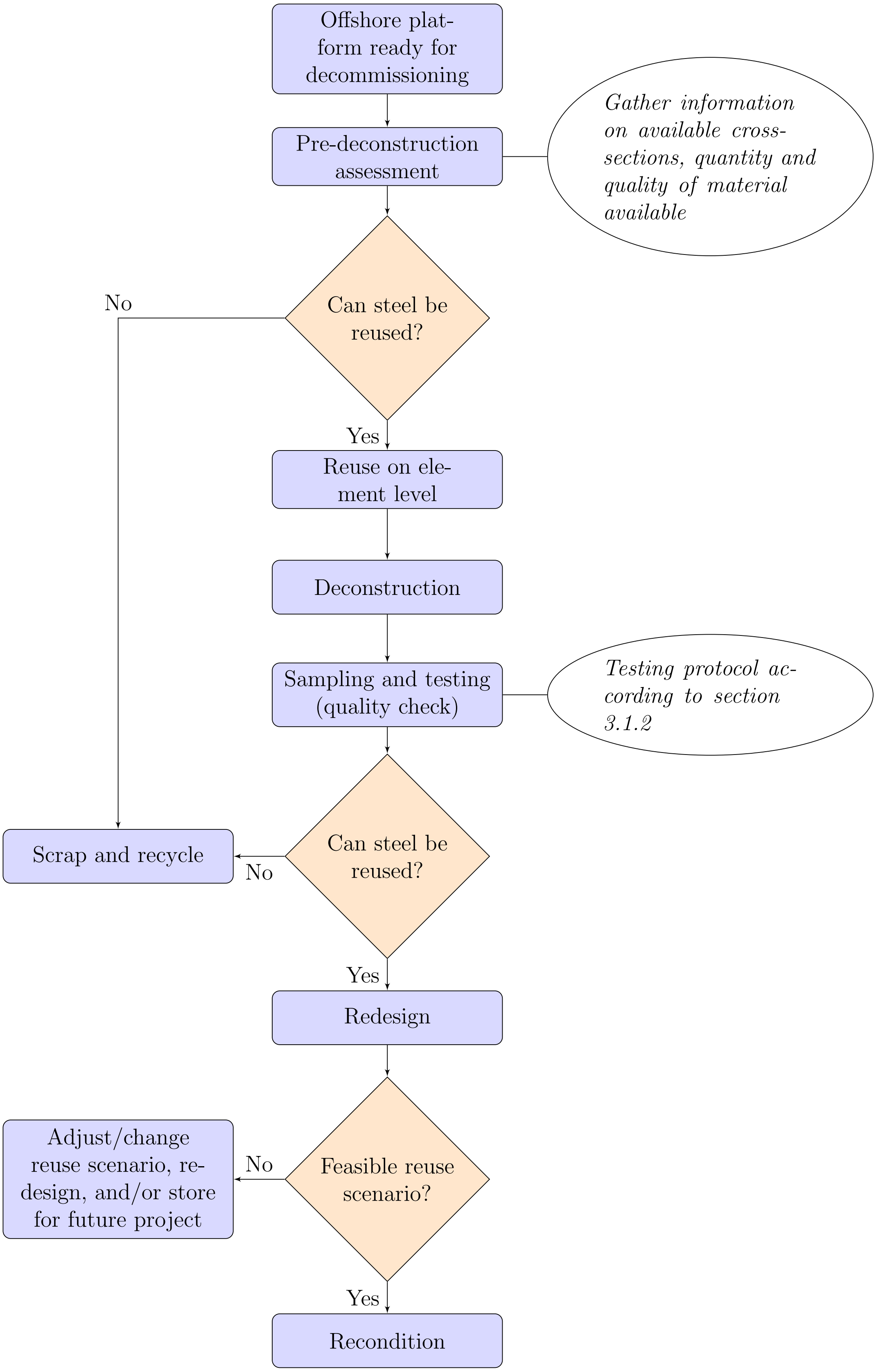


Figure 3.1: Outline of proposed reuse process for steel elements from offshore structures

The preponderance of work in the reuse process lies within the sampling and testing-part, as the demand for sufficient quality control is higher when the pre-used steel is coming from the offshore industry. This is due to the fact that offshore platforms are exposed to a more damaging environments than onshore steel structures. A comprehensive testing procedure is presented in Chapter 3.1.2.

3.1.2 Testing protocol

Following is a proposed testing protocol for quality verification of pre-used steel elements from offshore installations.

The scope and thoroughness of the testing procedure strongly depends on whether the quality of the pre-used elements can be verified by original certification (or otherwise valid documentation) or not. What constitutes valid certification is described below. If documents confirming the quality is available, it is recommended to do a visual inspection to detect any imperfections, followed by a hardness test to confirm the yield- and ultimate strength stated in the documentation. Furthermore, a non-destructive test of the chemical composition of the material should be performed. If the test confirms the chemical composition and alleged strength without too large of a deviation according to relevant standards for delivery conditions (EN 10025-2 [8] or EN 10346 [9] dependent on production method, excluding high strength structural steel), the element is cleared for reuse, otherwise it will be scrapped.

If however the original documentation is not available, there must be performed a series of comprehensive inspections to reveal 1) what type of steel component it is and 2) what condition the element is in. Once the geometry and the condition are verified, the steel can be subjected to thorough quality testing to be re-certified. This testing includes both non-destructive testing (NDT) and destructive testing (DT) to reveal the mechanical properties and chemical composition of the material. Results from NDT and DT must be consistent to be valid. If the result of this kind of test procedure proves the steel to be of insufficient quality, it will be scrapped and recycled. Figure 3.2 displays an overview of the testing procedures.

Documentation of steel elements

Certification of load carrying structural steel members is a method of verifying the quality of the components used in the construction industry. This certification documents must include information on requirements defined by EN 10025, such as mechanical properties, chemical composition, technical requirements (weldability, formability, machinability), surface properties, shape/dimensions and tolerances. Original drawings of the steel component/detail alone is not considered valid documentation on the above mentioned properties, however, it may prove useful in the redesign phase of the reuse process.

Grouping and sampling

When large quantities of steel elements that is considered for reuse, it is recommended to do statistical testing, i.e., choose a smaller selection of specimens to represent the whole batch of steel elements. To do so the elements must be divided into groups or test units based on certain requirements. The European Convention for Constructional Steelwork (ECCS) [4] suggests the following requirements to be met:

- Structural steel erected after 1970
- Similar serial size
- Same structural function (beam, column, stiffener, etc.)
- Identical detailing (length, connections etc.)
- Local stiffeners are not considered as detrimental for grouping

It is also suggested that the source and manufacturing standard of all specimens in a group should be consistent, and not exceed a combined maximum weight of 20 tonnes (4 tonnes for cold formed steel).

Inspection methods

If indeed a steel member is damaged/deformed/deteriorated, it is beneficial to label it as unusable as soon as possible, to not waste time and resources on it through further consideration. It is for that reason advisable to have clearly defined inspection methods which will be executed early on in the testing phase. Following is a list of possible inspection methods that can be utilized in a quality assessment:

- **Visual inspection** - Visual examination according to EN 13018 [10] with the purpose of uncovering corrosion, cracks, permanent deformation, and otherwise compromising damage that would affect strength, durability and permeability.
- **Geometrical inspection** - Examination of geometry of members with the purpose of determining cross-section dimensions, expose initial imperfections, check for deformation/deflection and check for modifications and/or repairs.
- **Dimensional inspection** - Accurate examination of dimensions using precise measuring equipment according to EN ISO 13385-1 [16] and EN ISO 13385-2 [17].

A visual inspection is required regardless of whether the original quality verification is available or not. Geometrical- and dimensional inspection is required when re-certifying the member, before comprehensive testing (NDT and DT). These inspections is also helpful in identifying locations from which to extract samples for the destructive testing.

Non-destructive tests

The purpose of non-destructive testing is to analyse and examine the properties of a specimen with minimal invasive actions, causing little to no damage. There are NDT methods that can test mechanical properties, as well as chemical composition of steel elements. NDT can be used to verify the available material certification, or in combination with DT form basis for re-certification. Relevant NDT methods with corresponding standards are listed below.

- **Hardness testing -** An object with specific dimension and composition is pressed against the surface of the specimen with a known force, leaving an imprint to be measured. The measurements provide basis for calculation of a hardness number. Yield- and ultimate strength can be estimated using hardness number. There are several approaches to this method of testing, each underpinned by internationally recognized standards. Vickers test method is mentioned in EN 1090-2
  Relevant standards:
  Vickers test method: ISO 6507-1 [14]
  Rockwell test method: ISO 6508-1 [15]

- **Instrumented indentation testing -** Similar approach as hardness testing, the only difference being load is being applied in cycles with increasing force. Indentation in the specimen is monitored and logged throughout the test, which form basis for calculating stress-strain relationship, elastic modulus, hardness and stiffness.
  Relevant standard:
  ISO 14577-5 [18]

- **Positive metal identification -** A device that uses x-ray fluorescence to determine the alloy composition of the steel specimen. It is essential to establish the chemical composition, which characterize the weldability of the steel. In particular the carbon-equivalent content, a key characteristic of the steel which is reflected in both strength- and weldability properties.
  Relevant standards:
  ISO 19272 [19]
  ASTM E572 [20]
  ASTM 1476 [21]

Destructive tests

Destructive testing obtains material properties by performing tests that damage the specimen. With DT it is necessary to do statistical testing to not damage to much of the overall structure. Specimens are extracted from the structure by drilling or cutting in locations which are expected to produce a representative result to the test, as well as not cause too much damage. DT is required in the absence of valid quality documentation. Relevant DT methods with corresponding standards are listed below.

- **Tensile testing -** Tensile test is performed on a representative set of samples from test unit(s). Output from this test is yield- and ultimate strength, modulus of elasticity and stress-strain relationship.
  Relevant standard:
  EN ISO 6892-1 [11]
- **Chemical composition analysis -** Testing the specimen for carbon content, and other alloy materials such as silicon, manganese, sulphur and phosphorus. Output of this test will determine weldability and purity levels. Test is done using drilling swarf from test specimen.
  Relevant standard:
  EN ISO 14284 [12]
- **Charpy impact test -** A pendulum/hammer is swung at the specimen, measuring the energy needed to break it at different temperatures. Results of this test gives an indication on brittleness and fracture toughness of the material, as well as characterize the steel sub-grade.
  Relevant standard:
  EN ISO 148-1 [13]
- **Metallography -** A microscopic examination of a specimen to determine internal structure (grain type, grain size and grain orientation).
  Relevant standard:
  ASTM E 112 [22]

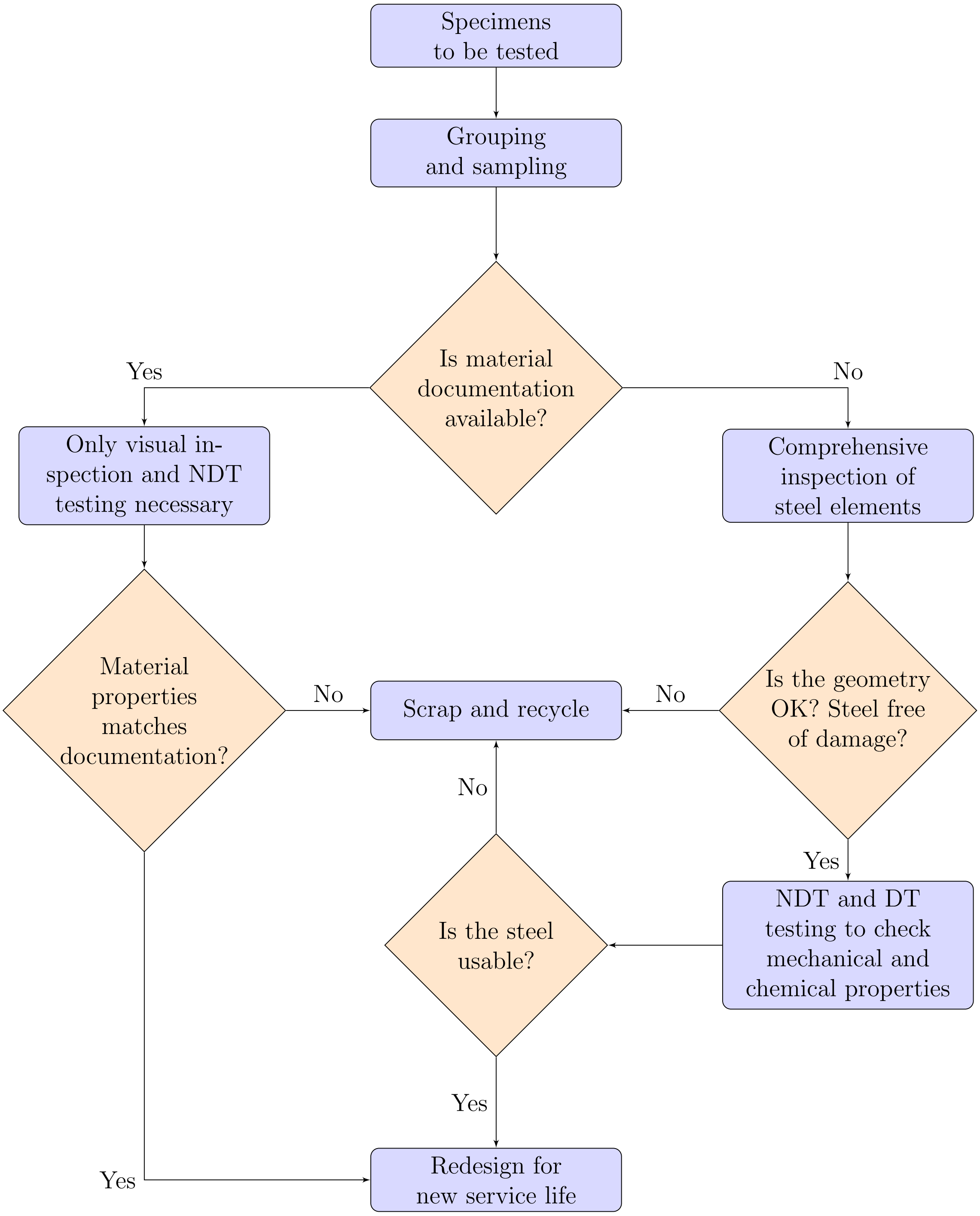


Figure 3.2: Testing protocol of pre-used offshore steel members

3.2 Modification of reusability index

The method of reusability index as presented in Chapter 2.2 is developed as a tool to quantify the difficulties connected to every aspect of the reuse process. Early case studies using this method dealt to a large extent with relocation of entire structures in different forms and examined and compared the index results with regards to reuse on element-, section-, and structural level. In this case study the objective is to utilize the reusability index as a tool to simply identify and quantify the feasibility for reuse of structural steel from offshore platforms, i.e. investigate possibilities for repurpose and reuse steel on an element level.

As shown in Table 2.1, the assessment criteria for reusability in this method are generic, and do not need modification to apply to any project, including this thesis' case study. However, the grades are divided by 20% increments, and the author takes the liberty to award intermediate ratings by 10% increments to allow for a more accurate feasibility study.

The weighting factors are analyzed and determined in Chapter 3.2.2.

3.2.1 Considerations on performance categories for offshore applications

Deconstruction

The deconstruction of offshore platforms for reuse is a complex operation. This procedure is a job made significantly easier if the platform is transported to shore before the disassembly process is undertaken. It is therefore assumed that the topside is transported to a dismantle yard onshore as described in Chapter 2.6.1. The reasoning behind this assumption is that when the platform reaches the end of its service life, it necessary to transport it to shore for recycling anyway. At the yard it is to a greater extent facilitated for a more streamlined dismantling of the structure than if it were to be dismantled in situ. However, even if the structure is transported to shore pre-dismantling, it is still a large job to deconstruct it without causing damage to the reusable members. In today's practice, when a platform is sent to a dismantle yard it is due for recycling, which allow for a demolition process using rough methods, such as less considerate cuts and explosives. This will not be possible when extracting members with the intention of reusing them. All of this has to be taken into account in both the assessment of the performance category and the weighting factor.

Separation and cleaning

The dismantling process would to a large extent revolve around using hand tools for cutting, as the details on the modules of platforms are mostly welded. After the members are removed it would require some cleaning of the cutting surfaces. Surface treatment of the members must also be expected. This includes removal of existing paint (sandblasting/brushing tools) and applying new layers of paint.

Handling and manipulation

This performance category includes on-site manipulation (mobility within the construction site), damage proneness, transport, and storage. Once individual members are removed from the structure, they would be easy to move using cranes and other lifting devices. Assuming the workers operate with some caution, the steel beams/columns/girders are not particularly prone to damage other than surface scraping and otherwise negligible damage. The members can be transported by road using lorries, by railway or by ship. A drawback in this performance category is the geographic challenges with regards to transport. There are only a certain amount of shipyards capable of taking on a workload of this magnitude, and the steel may have to be transported over large distances to reach the new site. Until a streamlined reuse industry is in place, storing steelwork for future projects is up to each individual contractor to handle, and is not relevant as of today.

Redesigning

The result of the redesigning performance category assessment depends on what documentation is available. This documentation includes original design documentation (drawings), documentation verifying material properties, maintenance history and loading history. Original drawings of offshore structures are generally available, additionally, the maintenance history is well documented by the company owning the platform. These documents describe the geometric properties, and any modifications that are done to the members. The loading history may be available for the jacket structure due to strain gauge surveillance but is usually not recorded for the topside members. However, to obtain loading history it is possible to replicate the structure in a 3D model (if 3D model is not already available) to perform a life cycle simulation of the loading history, which would be relevant for a fatigue damage assessment as described in Chapter 2.3.2. Documentation containing verification of material properties and general quality certification is covered in the quality check-category.

Repurposing

The result of the repurposing assessment reflects how suitable the member is in the new structure. When reusing on an element level, the individual members are extracted from the structure, and even though the geometry and size may stray from the standard dimensions of new production steelwork, it is possible to account for this in the design of the new structure with the proviso that there is a large quantity of members with consistent geometry and size available.

Modification

Once extracted, the steel members may need to be modified before being used. Considering the beams/columns/girders are cut from the donor platform, the only modifications needed are adding/adjustment of bolt holes, trim leftover welds and cuts to obtain the required lengths.

Quality check

The quality check category can have significant impact on the reusability assessment. The result of the assessment in this performance category largely depends on whether the proper documentation is available. If it is, the job of verifying what the documentation states is far less comprehensive than if it is not. This is further elaborated in Chapter 3.1.2.

Geometry check

This performance category contains a relatively small workload that can be done in the dismantling yard. This includes verifying position of any potential boltholes, as well as checking the length and straightness of member. Straightness can be measured visually or using lasers where it is necessary.

3.2.2 Weighting factors

The result of a reusability index-method analysis is case-dependant. The reusability depends on both the feasibility of extracting elements from the donor structure, as well as the feasibility of reusing the material in the new structure. The outcome of all the above-mentioned categories can prove decisive when determining the feasibility, and the economic and environmental profitability in a reuse project. The weighting factors rank the importance of what categories that should be emphasized in a particular project. They are also a reflection of the amount of work that goes into each category. The sum of the weighting factors w_i is equal to 1, which multiplied with the result of the category assessment in itself ρ_i generates a reusability index r as a percentage of reusability between 0 and 1.

This thesis bases itself on the weighting factors presented in [23] and [37]. These articles define the weighting factors based on case studies for reuse and relocation of onshore structures for different compositions of load bearing component classes. Reference weighting factors for onshore applications is listed in Table 3.1.

Table 3.1: Reference weighting factors

Reference	**[23]**	**[37]**
Perfomance category	w_i	w_i
Deconstruction	35%	30%
Handling and manipulation	10%	15%
Separation and cleaning	10%	10%
Redesigning	10%	10%
Repurposing	10%	5%
Modification	10%	10%
Quality check	10%	15%
Geometry check	5%	5%

The assessment of reusability of offshore structures is based on different presumptions than when assessing onshore structures. A presumption in onshore reusability analyses is that a lot of the workload is done in situ, while in offshore situations, the structure is transported to a dismantle yard where the conditions are more conducive for the work. Cranes, tools, machinery, and other equipment that is required for the practical work is available at the yard, laying the foundation for an effective and streamlined operation. This will affect the performance category assessment and the weighting factors.

As displayed in Table 3.1, the deconstruction performance category is identified as the main- and most feasibility-defining work package of the assessment in onshore reusability analyses, while the other categories are awarded a more even weighting distribution. Due to the above-mentioned reasons, the weighting of deconstruction can be adjusted down to leave room for the more challenging aspects of offshore reuse. The quality check procedure has the potential to significantly increase the workload and time consumption of the entire process due to its uncertain nature and should therefore be awarded a higher weight-rating. Furthermore, during an offshore service life the steel members are subjected to harsh marine environments. This increases the importance of a thorough and precise quality verification.

The modification performance category should be weighted lower than the reference. The reason being that reusing beams and columns on an element level requires less planning and work than reusing on a section- or structural level.

The rest of the performance categories should be weighted in somewhat the same manner as the reference weighting in Table 3.1. Proposed modified weighting factors for reusability assessment of offshore structures is listed in Table 3.2.

Table 3.2: Proposed weighting factors for reusability assessment of offshore structures

Perfomance category	w_i
Deconstruction	25%
Handling and manipulation	10%
Separation and cleaning	10%
Redesigning	10%
Repurposing	5%
Modification	5%
Quality check	30%
Geometry check	5%

Chapter 4

Case study

4.1 Project presentation

The data presented in this thesis is substantiated by a case study provided by the Sweco Porsgrunn office. The objective of the case study is to utilize the information gathered in a close to real-life situation. The project chosen (in cooperation with Sweco) for this thesis is an apartment building which are part of a bigger housing development program called Nybyen in the city of Sandefjord.

Figure 4.1: 3D model of load bearing structure LG6, Nybyen

The building which is located in Langes gate 6 (LG6) will contain 11 apartments distributed among four floors (not including the car park in the basement). The building is made up of concrete floors supported by steel columns, as depicted in Figure 4.1. The reason for choosing this project is the commonness of this type of building, which means that it is applicable for a large number of similarly sized construction projects where reusing steel is a possibility.

Table 4.1 contain a list of all new designed steel columns in LG6. More detailed lists containing lengths, masses etc. is attached in Appendix A. The lengths of the columns corresponds with the floor heights of approximately 2,7m, and the steel grade is S355. The total mass of the 69 steel columns adds up to 5 220 kg.

Table 4.1: List of steel columns in LG6, Nybyen.

Column type	**Quantity**
RHS150x100x8	9
RHS150x100x10	15
RHS200x100x10	5
RO139.7x8	12
SHS100x8	14
SHS100x10	14
Total:	**69**

4.2 Loads

The columns listed in Table 4.1 are subjected to normal forces in the form of dead load, imposed load, and environmental load. They are considered to be fixed at the top and bottom and carry bending moment due to load coming from the concrete floors. Also present is a small amount of wind load which contributes to the bending moment. The loads are analysed in the ultimate limit state (ULS), and are calculated using FEM software. Floor plans showcasing the loads on the current columns and corresponding utilization ratio is attached in Appendix A. The utilization ratio takes into account axial loads and reduced axial capacity in combination with bending moment. This case study will consider and analyze the columns with loads > 400 kN and/or utilization ratio of current cross-section > 70%. These limits are set to identify the columns which are subjected to the most critical load combinations of axial load and bi-axial bending. Relevant columns are listed in Table 4.2. Axial load N_{Ed} is listed in kN, bending moment $M_{i,Ed}$ is listed in kNm, and locations are listed in correspondance with Figures A.1-A.8 in Appendix A. Parentheses in the location column denotes floor level in the building.

Table 4.2: Dimensional loads on new steel columns

Location	**Column type**	N_{Ed}	$M_{y,Ed}$	$M_{z,Ed}$	**Utilization ratio**
C/4 (2)	RHS200x100x10	594,4	12,81	3,56	85,3 %
B/4 (2)	RHS200x100x10	850,1	18,21	0,56	98,3 %
A.6+1/3.11 (2)	RHS200x100x10	729,0	0,79	5,49	81,3 %
A.6+2/1+ (2)	RHS200x100x10	697,3	0,90	4,87	76,7 %
B+1/1 (2)	RHS150x100x10	438,4	1,64	7,79	67,5 %
B+2/1 (2)	RHS200x100x10	595,9	1,48	13,83	73,8 %
C/4 (3)	RHS150x100x10	429,3	17,84	17,46	93,1 %
B/4 (3)	RHS150x100x10	607,5	11,33	14,95	97,9 %
A.6+1/3.11 (3)	RHS150x100x10	504,8	2,43	5,93	73,8 %
A.6+2/1+ (3)	RHS150x100x10	474,4	1,19	4,79	68,2 %
B+2/1 (3)	RHS150x100x10	443,1	1,22	12,86	71,7 %
C/4 (4)	SHS100x100x10	273,8	8,14	11,85	83,3 %
B/4 (4)	SHS100x100x10	388,3	4,62	9,64	88,0 %
C/4 (5)	SHS100x100x8	126,8	8,17	11,07	76,6 %

4.3 Availability check

It is common for the topside of an oil platform to consist of smaller modules that can be built in a shipyard and transported out to the site for further assembly. This case study has considered one of these modules from a decommissioned oil rig as a potential donor structure. The platform was located in relatively shallow water, and was fixed to the seabed. Due to data confidentiality issues, the name of the platform and the company for which it served will not be mentioned.

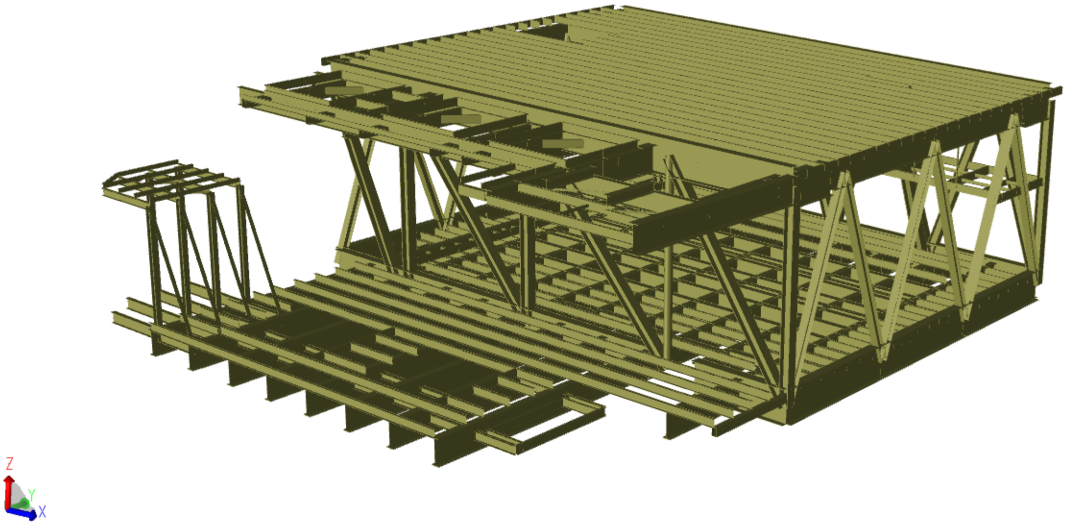


Figure 4.2: Model of M4W platform module

The module is made exclusively by steel and consists of large I-beam girders, transverse flooring beams, and stiffening members. The floors are carried by angled H-columns, and all joints are welded. The relevant cross sections for reuse as columns in an apartment building are these H-columns, due to their sizes and dimensions. Original drawings and maintenance history is available, while material documentation is not. The four relevant and available types of columns are listed below. More detailed overview of geometrical cross sectional properties is attached in Appendix B. These columns were chosen based on the assumption that they are best suited to withstand axial loading and bi-axial bending moment.

- **UC 305x305x97**

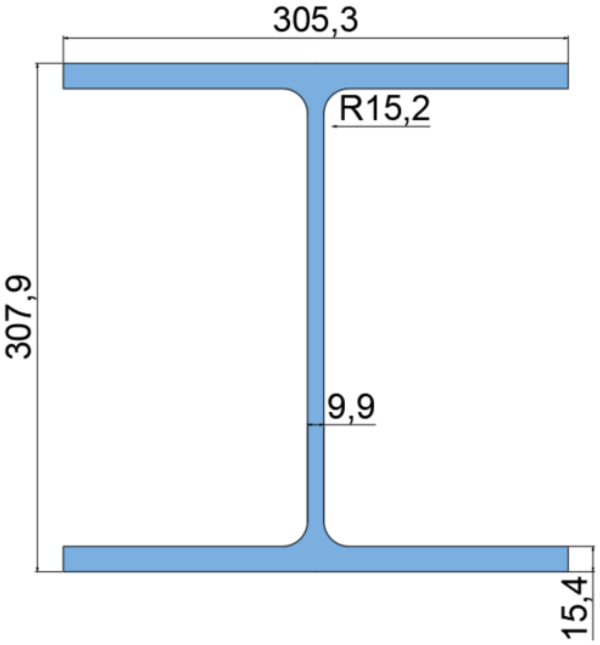


Figure 4.3: UC 305x305x97

- **UC 356x406x235**

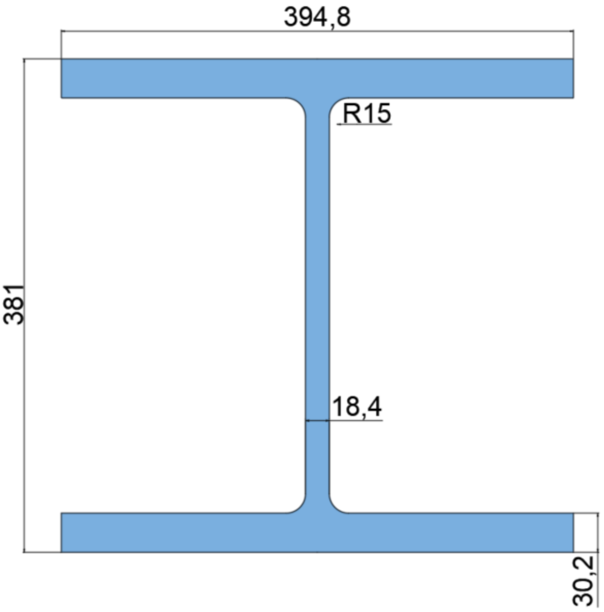


Figure 4.4: UC 356x406x235

- **UC 356x406x287**

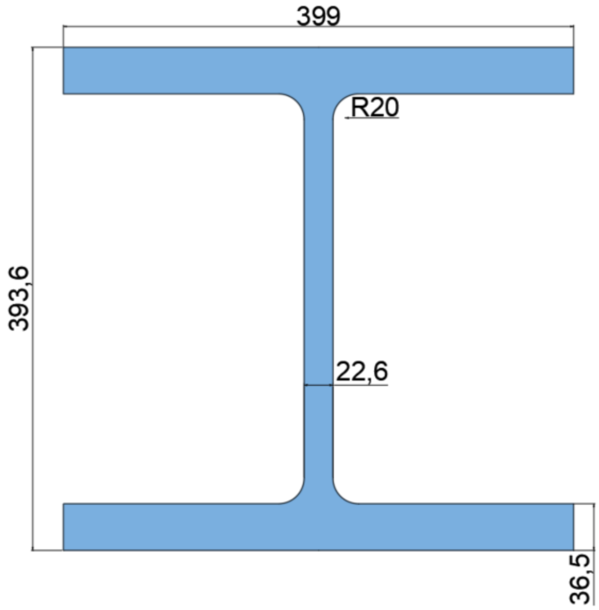


Figure 4.5: UC 356x406x287

- **UC 356x406x393**

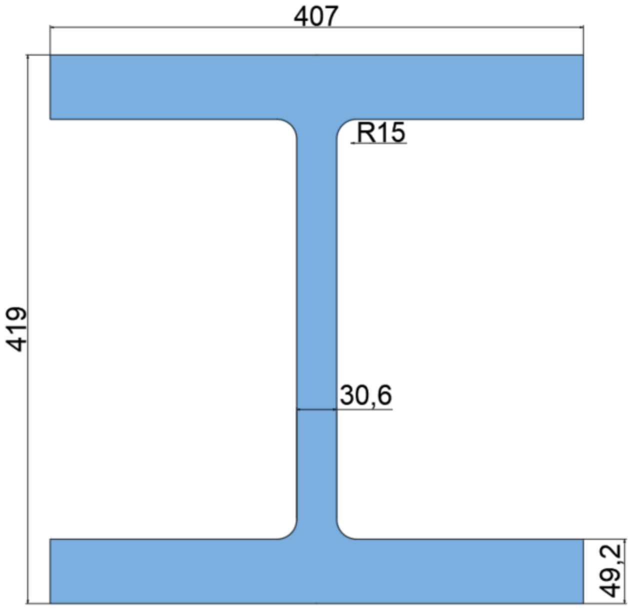


Figure 4.6: UC 356x406x393

4.3.1 Cross-section properties

The material of the columns is grade 40EE. The yield strength in this steel grade is is listed in the British standard specification for weldable structural steels BS 4360 [38] and depends on the type of cross-section and thickness t. The cross-sections are classified according to section 5.2 in EN 1993-1 [39]. Compressive loading capacity is calculated using equation 6.10, which is quoted in Equation 4.1 below.

$$N_{c,Rd} = \frac{Af_y}{\gamma_{M0}} \tag{4.1}$$

Where A is cross sectional area, f_y is yield strength, and γ_{M0} is the material safety factor set equal to 1.05 according to national annex of NS EN 1993.

Table 4.3: Material and geometric properties of UC columns from M4W module

	305x305x97	**356x406x235**	**356x406x287**	**356x406x393**
Steel grade	40EE	40EE	40EE	40EE
Maximum t (mm)	15,4	30,2	36,5	49,2
f_y (N/mm^2)	260	245	245	240
ε	0,951	0,979	0,979	0,990
Flange class	2	1	1	1
Web class	1	1	1	1
C/S class	2	1	1	1
$N_{c,Rd}$ (kN)	3055,8	6976,7	8563,3	11442,3

The values in Table 4.3 are based on the assumption that the column only are subjected to axial load. In reality, they are subjected to both axial load and bending moment due to moment carrying joints, loading eccentricity and wind load. To accurately determine the capacity of the columns, it is necessary to perform calculations described below.

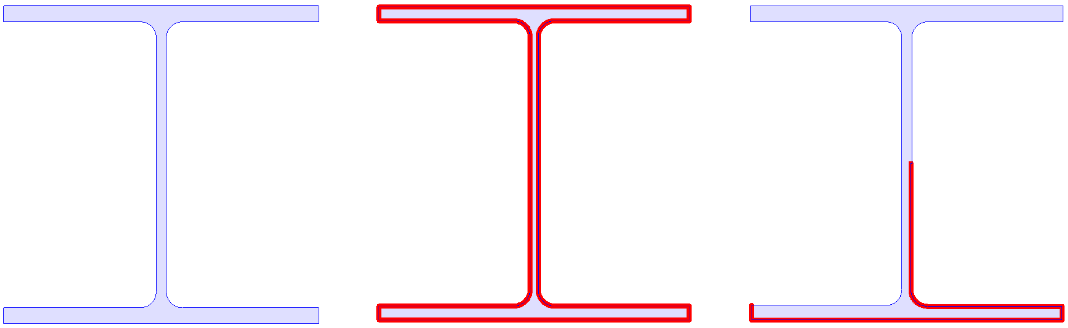
Bending and axial load

In combination with axial loading, bending moment reduce the axial loading capacity of a column. Section 6.2.9 and 6.3 in EN 1993-1-1 [39] describes the method of determining whether a cross section can withstand bending and axial load. This is a tedious and slow process to do by hand, and is preferably done in FEM software.

4.4 Degradation of columns

There should be accounted for some degradation damage on the columns listed in Chapter 4.3. Considering the columns are extracted from the topside of a fixed platform, there is an argument to be made that accumulated fatigue damage is negligible, which means that corrosion is the primary degradation mechanism to consider. This being a theoretical case study, it is reasonable to assume different cases of corrosion damage ranging from no degradation up to and including a worst-case scenario. The cases are based on a conservative consideration of uniform corrosion accumulation according to corrosion depth equations presented in Chapter 2.3.1.

- **Case 1 -** No corrosion.
- **Case 2 -** Uniform corrosion along the whole cross-section.
- **Case 3 -** Uniform corrosion along parts of the cross-section, creating eccentricity and additional bi-axial bending moment.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 4.7: Corrosion cases

Figure 4.7 depicts the UC 305x305x97 column with the different corrosion cases. The platform in question is assumed to have a lifespan of $t = 25$ years. In case 2 the protection time t_{pt} is set to be 10 years, which gives 15 years of corrosion development. This is a conservative estimate, considering the columns in question are not directly exposed to the marine environments. In case 3 the protection time t_{pt} is set to be 0. The governing factor behind this assumption is that the columns can be exposed to a corrosive environment on one side due to discontinuity in the protective layer, or otherwise corrosive enhancing elements such as dirt, water, or other foreign bodies. The corrosion depth $W(\Delta t)$ is calculated using Equation 2.3 with model parameters A and B from ”Severe corrosion found” from Table 2.2. Corresponding geometrical properties is listed in Table 4.4.

Table 4.4: Geometrical properties for different corrosion cases UC 305x305x97

	Case 1	**Case 2** ($\Delta t = 15$)	**Case 3** ($\Delta t = 25$)
$W(\Delta t)$ (mm)	0	1,0	1,5
C/S area (mm^2)	12345	10559	11462
e_z (mm)	0	0	11
e_y (mm)	0	0	2

Result of capacity calculation with regards to axial load, bi-axial bending moment and corrosion cases is presented in Chapter 5.1.1.

4.5 Performance category assessment

Based on the data presented in Chapter 3.2 and the criteria in Table 2.1, the performance categories ranking is determined and listed in Table 4.5. The feasibility values of the performance category ρ_i leans toward the conservative side.

Table 4.5: Proposed performance category ranking for M4W columns

Category	ρ_i	**Comment**
Deconstruction	0,5	Welded connections, moderately difficult access
Handling and manipulation	0,6	Manipulation by crane, forklift and small lifting devices
Separation and cleaning	0,4	Separation and cleaning using hand tools
Redesigning	0,8	Detailed drawings and maintenance history available
Repurposing	0,4	Some remanufacturing required
Modification	0,6	Columns are applicable for reuse without too much work
Quality check	0,4	Material documentation not available, require laboratory testing
Geometry check	0,8	Simple straightness testing using lasers

4.6 LCA

The life cycle assessment of this case study is performed in One Click LCA [40]. This is a software that utilizes environmental product declarations (EDP) to calculate the global warming potential (GWP) of construction projects according to NS 3720:2018 [41]. It accounts for every source of CO_2-emissions for all building materials throughout the life cycle phases described in Figure 1.1.

In this case study the area of interest is the steel columns, and the assessment will analyse the GWP of these alone. The EPD for the RHS columns used in this analysis is from the Norwegian steel manufacturer Tibnor [42]. For the reused UB 305x305x97 columns, a generic EPD for H-sections has been utilized with a reuse function added to it. The other input parameter is the total mass of the steel columns, which has been inserted in both cases. Results of the LCA analysis is presented in Chapter 5.1.3.

Chapter 5

Results and discussion

5.1 Results

5.1.1 Column capacities

This thesis utilizes FEM-Design 21 for the capacity calculations. The columns listed in Table 4.2 were substituted with UC 305x305x97 and steel grade changed to 40EE in the model, and analyzed according to NS EN 1993-1-1 [39]. Results are presented in Table 5.1.

Table 5.1: Utilization of UC 305x305x97 columns from M4W module

Location	N_{Ed} (kN)	$M_{y,Ed}$ (kNm)	$M_{z,Ed}$ (kNm)	**Utilization ratio** (%) **Case 1**	**Case 2**	**Case 3**
C/4 (2)	594,4	12,81	3,56	33	42	40
B/4 (2)	850,1	18,21	0,56	38	49	47
A.6+1/3.11 (2)	729,0	0,79	5,49	29	36	34
A.6+2/1+ (2)	697,3	0,90	4,87	27	34	32
B+1/1 (2)	438,4	1,64	7,79	19	24	22
B+2/1 (2)	595,9	1,48	13,83	28	35	32
C/4 (3)	429,3	17,84	17,46	29	33	32
B/4 (3)	607,5	11,33	14,95	31	38	35
A.6+1/3.11 (3)	504,8	2,43	5,93	21	26	25
A.6+2/1+ (3)	474,4	1,19	4,79	19	24	23
B+2/1 (3)	443,1	1,22	12,86	22	27	25
C/4 (4)	273,8	8,14	11,85	18	21	19
B/4 (4)	388,3	4,62	9,64	19	23	22
C/4 (5)	126,8	8,17	11,07	12	14	12

In addition to N_{Ed} and $M_{i,Ed}$, there is additional bending moments as a result of eccentricity (case 3 only) about both y-y and z-z axes. Eccentricity induced bending moments corresponds with N_{Ed} and eccentricity as listed in Table 4.4. The utilization ratio is listed as the maximum of utilization ratios in the following categories with corresponding sections in NS EN 1993-1-1:

- Cross-section resistance (6.2.1-6.2.8)
- Flexural buckling (6.3.1)
- Torsional-flexural buckling (6.3.1)
- Lateral torsional buckling (6.3.2.4)
- Interaction (6.3.3)

As depicted in Table 5.1, the highest utilization ratio occurs in column B/4 (2) in corrosion case 2 with 49%. Considering UC 305x305x97 is the smallest column identified as suitable from the M4W module, similar analysis of the other three larger cross-section is redundant.

5.1.2 Reusability index result

Table 5.2 combines Tables 4.5 and 3.2 and using Equation 2.1 to produce a reusability index r for the available columns of the M4W module.

Table 5.2: Reusability index for M4W columns

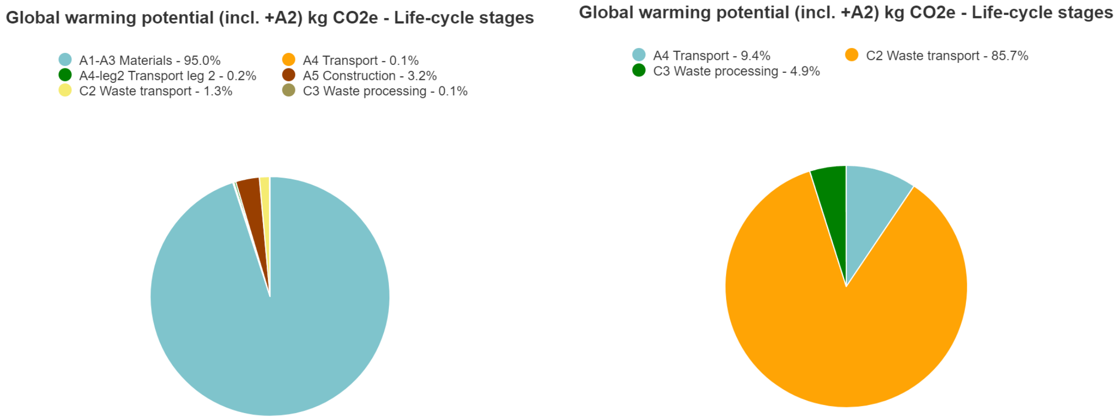
Category	ρ_i	w_i	$\rho_i w_i$
Deconstruction	0,5	0,25	0,125
Handling and manipulation	0,6	0,10	0,06
Separation and cleaning	0,4	0,10	0,04
Redesigning	0,8	0,10	0,08
Repurposing	0,4	0,05	0,02
Modification	0,6	0,05	0,03
Quality check	0,4	0,30	0,12
Geometry check	0,8	0,05	0,04
$r = \Sigma \rho_i w_i$			**0,515**

5.1.3 LCA result

For a simple LCA analysis such as the one in this thesis where the objective is to compare two sets of columns in a building, the input parameters are EPDs and masses, as well as method of transport and transport distance. In the analysis it is assumed that only the square and rectangular hollow sections are being substituted with UB 305x305x97 cross sections, as the circular RO139.7x8 sections supporting the balconies of the building are quite small in comparison. These would preferably be substituted with more similarly sized cross sections for both structural and aesthetic reasons. The transport distances are based on the geographical locations of Tibnor (the steel manufacturer providing the EPD for the hollow sections) and the Aker Solutions shipyard in Stord relative to the apartment building in Sandefjord. It is assumed the steel is transported by road on lorries. Table 5.3 shows the input parameters and result of the LCA analysis. Figures 5.1a and 5.1b displays the distribution of GWP for the new and reused columns respectively.

Table 5.3: Input parameters and result of LCA analysis

	New steel	**Reused steel**
Mass (kg)	5220	14928
Assumed transport distance (km)	185	430
Global warming potential ($kgCO_2$)	14838	667



(a) GWP for current RHS columns (b) GWP for reused UB305x305x97 columns

Figure 5.1: LCA result

5.2 Discussion

Design optimization

Table 5.1 shows that the M4W columns analysed in this thesis' case study has more than sufficient capacity to withstand the loads they would be subjected to in LG6. This shows that columns such as the ones from the M4W module is applicable for structures which are of the same size, and larger than that of this thesis' case study. Data presented in Table 5.1 also displays the possibility for allowing for some degradation due to corrosion in the design, given the residual capacity is sufficient, and the column is treated and protected against further corrosion development.

For future references, it is beneficial to investigate a larger pool of steel components from decommissioned oil platforms in order to obtain columns more suited to the specific project. In this regard, an overarching principle would be to identify and use columns which yields a utilization ratio closer to 100%, as is the practice in the construction industry in general. This will optimize the design, and lead to cost reduction in procurement of materials.

An alternative way to approach the design process with pre-used steel elements is to change the structural configuration of new buildings to suit the capacity of available columns. In general this would include changing span lengths, column heights, and alternate the way the loads are transferred through the structure. These changes in structural configuration would enter into the modification performance category in the reusability index.

Feasibility

The reusability index-method analyses and quantifies the practicality of steel reuse. The limitation of this method is that it only gives an indication on how feasible implementation of reuse is, i.e. it is not exact science. However, with enough input data and background research it is possible to obtain a fairly accurate pointer as to how reusable an element/group of elements are. In this case study reusability r is calculated using Equation 2.1 which only is valid for single steel elements, but as the deciding factors of the reusability assessment (performance categories and weighting factors) are determined on the same basis for all the columns in the M4W module, it is reasonable to treat them as one single unit.

Table 5.2 displays a $r = 51,5\%$ for the columns of the M4W module, which hardly is an indication of a profitable reuse operation. In order to obtain a larger r-value, the drawbacks must be identified and addressed. The features with the most potential for improvement in this regard are the low-scoring performance categories with the largest corresponding weighting factors, i.e, the deconstruction- and the quality check performance categories in this case.

Environmental and economic perspective

The result of the LCA analysis in the case study indicates significant environmental benefits with regards to global warming potential. Table 5.3 shows that when using new steel columns with a total mass of 5220 kg the GWP yields emissions of 14838 kg CO_2. The reused columns with a total mass of 14838 kg yields only 667 kg CO_2. This gives a GWP to mass ratio of 2.84 kgCO_2/kg for the new steel, and 0.04 kgCO_2/kg for the reused steel. This result can only be considered to be an indication, as there are uncertainty associated with the GWP distribution from the software. The reuse function in the software neglects the GWP associated with re-manufacturing and construction, as can be seen in Figure 5.1b.

Another aspect to consider is the fact that this LCA analysis is concentrated around this particular construction project. Not only does the GWP for the reused steel not account for re-manufacturing and construction, but in the process of reusing offshore steel there are a number of additional emission sources that should be taken into account, such as transport to shore (would be necessary anyway), dismantling, and storage. In this regard it would be beneficial to have an EPD specifically made for reused steel from offshore structures, to obtain a more accurate GWP. There is also an argument to be made that the original production of steel should be included, so that the emissions throughout all of the service lives of the steel is accounted for. On the other hand, when the alternatives for the decommissioned offshore platform is either remelt or reuse, it may be sensible to focus on the fact that the reuse removes the remelting step and related emissions.

The process of determining how profitable it is to reuse steel from offshore structures in terms of money is currently a difficult one, considering there is no marketplace for it. This is also the reason why it can be assumed that it is not very profitable. Determining cost of reused steel in this thesis' case study would require approaching the parties in the supply chain, and create a full cost breakdown structure (CBS). Once a CBS is in place, the cost and potential savings can be calculated as described in Chapter 2.4.

Chapter 6

Conclusions

6.1 Summary and conclusions

This thesis has taken on the issue of feasibility regarding reuse of structural steel from decommissioned offshore platforms. The theory presented in Chapter 2 is all based on current standards, guidelines and recommended practices. There have been presented an overview of relevant standards and guidelines related to inspection, material and geometrical requirements and design. The thesis has also presented the theoretical basis of corrosion damage and fatigue damage, and how to reuse steel members that have been subjected to these degradation mechanisms.

To quantify the reusability of steel from offshore platforms, a reusability index has been presented and modified to also apply to offshore structures. This has been utilized in a case study to investigate the possibility of reusing offshore steel in a real-life situation. The case study revealed a reusability index r of 51,5%, which leaves room for improvement with regards to economic considerations and sustainability. In order to increase reusability r there must be made some changes in the decommissioning process to industrialize and streamline the supply of reused offshore steel in the construction industry. These changes can be summed up in the following criteria:

- **Decommissioning -** Facilitate the shipyards to be able to deconstruct the platforms in a way in which the steel members are reusable afterwards.
- **Refurbishing -** Incorporate stockists in the steel supply chain that specializes in the refurbishing process, and also have capacity for quality check through laboratory facilities.
- **Logistics -** Establish a competitive logistics network with capacity for storing- and transporting the pre-used steel.

It would be beneficial if the companies running the deconstruction yards could take on these three additional workloads, as this would save time and transportation costs. This is reflected in the proposed weighting factors, where the deconstruction and quality check are the most decisive work loads. To centralise the workloads of the reuse process would go a long way to making reuse of offshore steel viable compared to new production steel.

Considering that pre-used offshore steel holds sufficient capacity for a large number of construction projects (as shown in Chapter 4), there is reason to believe that if these three criteria are met, there would be a market for pre-used steel offshore in the construction industry.

6.2 Further work

Following is a list of suggestions of how to proceed with the research with regards to reusing steel from offshore platforms.

- Tailor reusability index performance category criteria to offshore reuse, assuming a streamlined operation is in place.
- Modify weighting factors based on statistics and hard data.
- Investigate what cross-sections may be available in the future.
- Develop an internationally recognized set of standards on inspection and testing as well as reuse with elements that have been subjected to degradation mechanisms.
- Design steel structures and elements (both onshore and offshore) for the purpose of reusing them.
- Develop EPD(s) for reused offshore steel.

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Appendix A

A.1 Steel columns in Nybyen

Table A.1: Detailed list of columns LG6, Nybyen

Column type	Length (mm)	Location
LG6 - PLAN 02		
RHS150x100x10	2700	LG6-4-LG6-A(1987)
RHS200x100x10	2700	LG6-4-LG6-B(-300)
RHS150x100x10	2700	LG6-1-LG6-C(433)
RHS150x100x10	2700	LG6-1-LG6-B(550)
RHS150x100x10	2700	LG6-1-LG6-B(-1714)
RHS150x100x10	2715	LG6-3(3113)-LG6-A
RHS150x100x10	2715	LG6-2(3128)-LG6-A
RHS150x100x10	2715	LG6-2(-3175)-LG6-A(1462)
RHS200x100x10	2700	LG6-1-LG6-C(-2779)
RHS150x100x10	2700	LG6-4-LG6-B(3000)
RO139.7x8	2690	LG6-4-LG6-A
RO139.7x8	2690	LG6-2(-175)-LG6-A
RO139.7x8	2690	LG6-1-LG6-A(1500)
RHS200x100x10	2715	LG6-3(3138)-LG6-A(1925)
RHS150x100x10	2715	LG6-2(3060)-LG6-A(1463)
RHS200x100x10	2715	LG6-2(-3237)-LG6-B(-1740)
RHS200x100x10	2700	LG6-4-LG6-C

Table A.1: Detailed list of columns LG6, Nybyen

Column type	Length (mm)	Location
LG6 - PLAN 03		
RHS150x100x8	2700	LG6-4-LG6-A(1987)
RHS150x100x10	2700	LG6-4-LG6-B(-300)
RHS150x100x10	2700	LG6-4-LG6-C
RHS150x100x8	2700	LG6-1-LG6-C(433)
RHS150x100x8	2700	LG6-1-LG6-B(550)
RHS150x100x8	2700	LG6-1-LG6-B(-1714)
RHS150x100x8	2715	LG6-3(3113)-LG6-A
RHS150x100x8	2715	LG6-2(3128)-LG6-A
RHS150x100x8	2715	LG6-2(-3175)-LG6-A(1462)
RHS150x100x10	2700	LG6-1-LG6-C(-2779)
RHS150x100x8	2700	LG6-4-LG6-B(3000)
RO139.7x8	2710	LG6-4-LG6-A
RO139.7x8	2710	LG6-2(-175)-LG6-A
RO139.7x8	2710	LG6-1-LG6-A(1500)
RHS150x100x10	2715	LG6-3(3138)-LG6-A(1925)
RHS150x100x8	2715	LG6-2(3060)-LG6-A(1463)
RHS150x100x10	2715	LG6-2(-3237)-LG6-B(-1740)
LG6 - PLAN 04		
SHS100x10	2715	LG6-3(3138)-LG6-A
SHS100x10	2715	LG6-2(3103)-LG6-A
SHS100x10	2715	LG6-2(-3200)-LG6-A(1462)
SHS100x10	2700	LG6-4-LG6-A(1962)
SHS100x10	2700	LG6-4-LG6-B(-300)
SHS100x10	2700	LG6-4-LG6-C
SHS100x10	2700	LG6-1-LG6-C(458)
SHS100x10	2700	LG6-1-LG6-B(550)
SHS100x10	2700	LG6-1-LG6-B(-1739)
SHS100x10	2700	LG6-1-LG6-C(-2779)

Table A.1: Detailed list of columns LG6, Nybyen

Column type	Length (mm)	Location
SHS100x10	2700	LG6-4-LG6-B(3000)
RO139.7x8	2710	LG6-4-LG6-A
RO139.7x8	2710	LG6-2(-175)-LG6-A
RO139.7x8	2710	LG6-1-LG6-A(1500)
SHS100x10	2715	LG6-3(3138)-LG6-A(1925)
SHS100x10	2715	LG6-2(3060)-LG6-A(1463)
SHS100x10	2715	LG6-2(-3237)-LG6-B(-1740)
LG6 - PLAN 05		
RHS150x100x10	2732	LG6-3-LG6-A
SHS100x8	2732	LG6-3(3138)-LG6-A
SHS100x8	2732	LG6-2(3103)-LG6-A
SHS100x8	2732	LG6-2(-3200)-LG6-A(1462)
SHS100x8	2717	LG6-4-LG6-A(1962)
SHS100x8	2717	LG6-4-LG6-B(-300)
SHS100x8	2717	LG6-4-LG6-C
SHS100x8	2717	LG6-1-LG6-C(458)
SHS100x8	2717	LG6-1-LG6-B(550)
SHS100x8	2717	LG6-1-LG6-B(-1739)
SHS100x8	2717	LG6-1-LG6-C(-2779)
SHS100x8	2717	LG6-4-LG6-B(3000)
SHS100x8	2732	LG6-3(3138)-LG6-A(1925)
SHS100x8	2732	LG6-2(3060)-LG6-A(1463)
SHS100x8	2732	LG6-2(-3237)-LG6-B(-1740)
RO139.7x8	2727	LG6-4-LG6-A
RO139.7x8	2727	LG6-2(-175)-LG6-A
RO139.7x8	2727	LG6-1-LG6-A(1500)

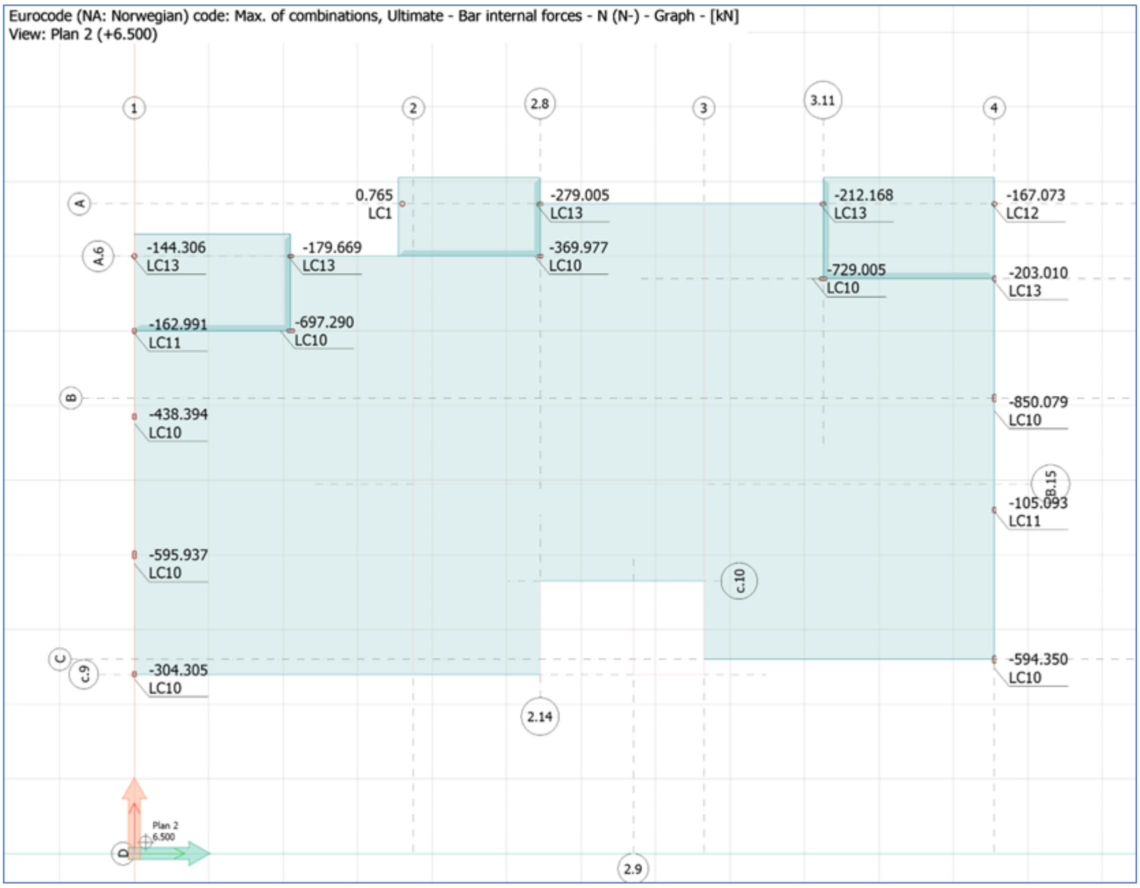

Figure A.1: Column loads, plan 02 in LG6

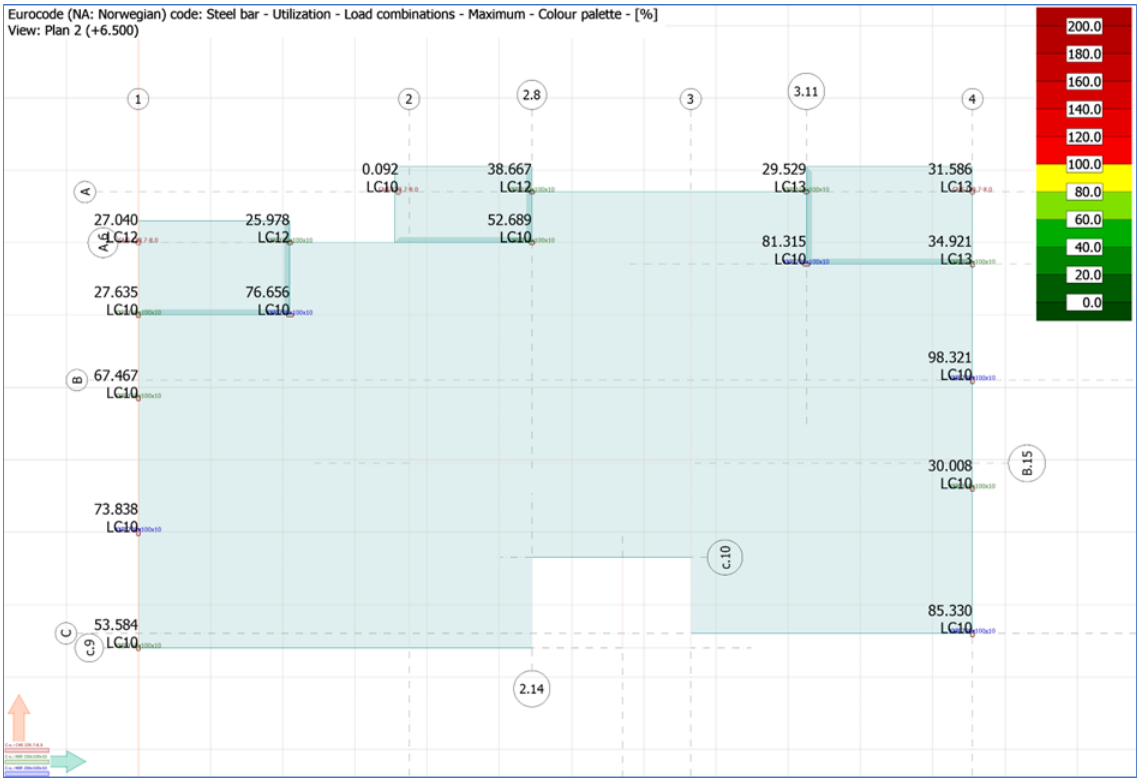

Figure A.2: Column utilization ratio in percent, plan 02 in LG6

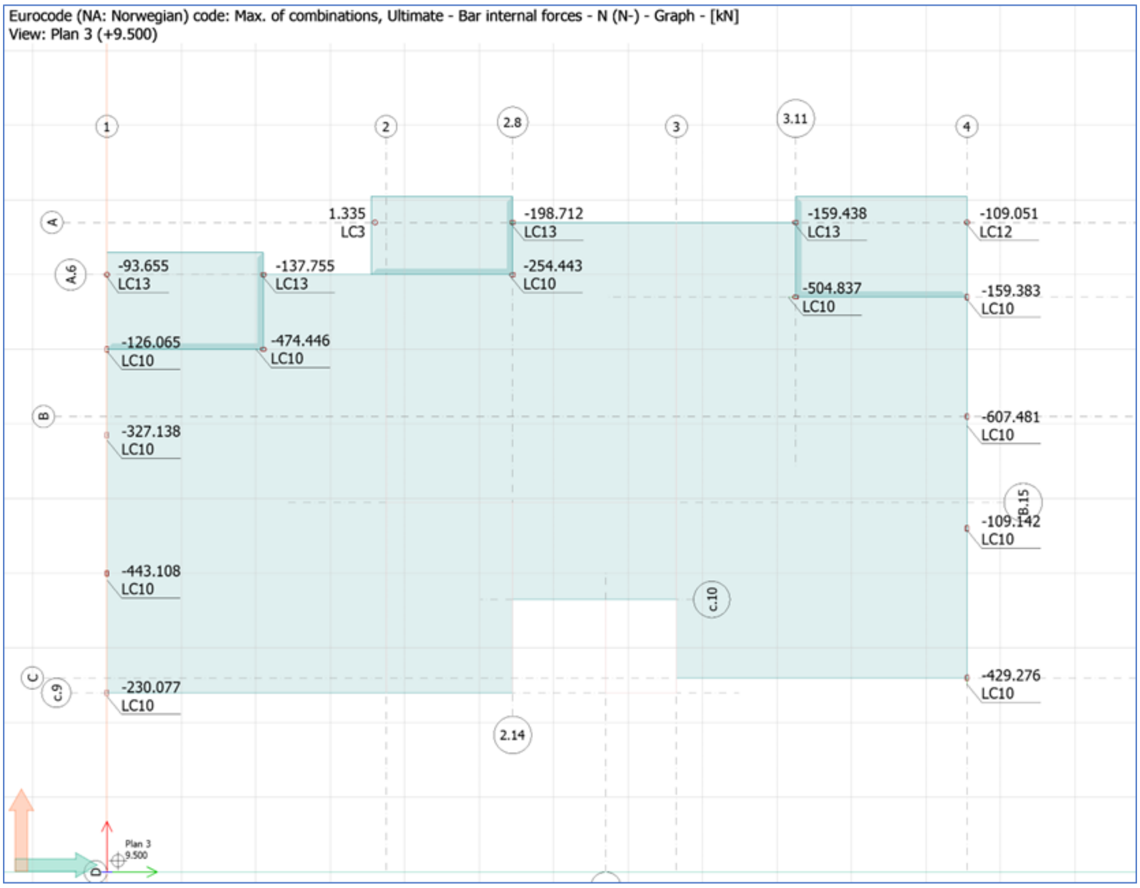

Figure A.3: Column loads, plan 03 in LG6

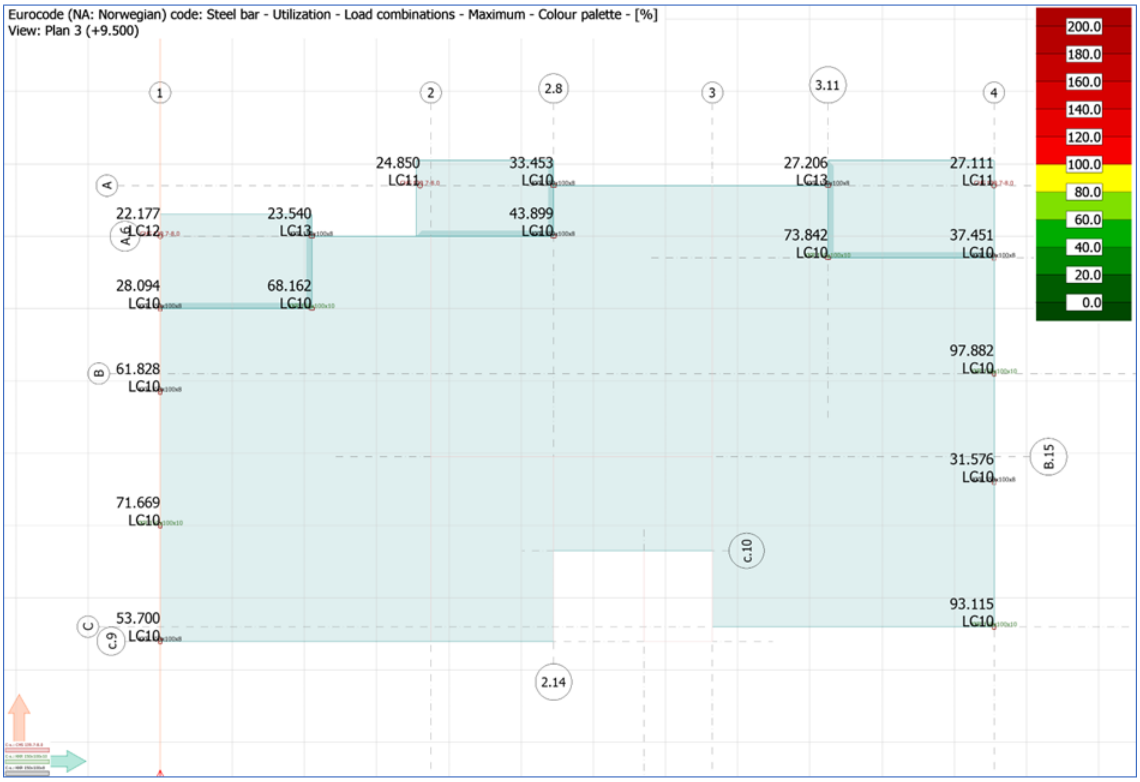

Figure A.4: Column utilization ratio in percent, plan 03 in LG6

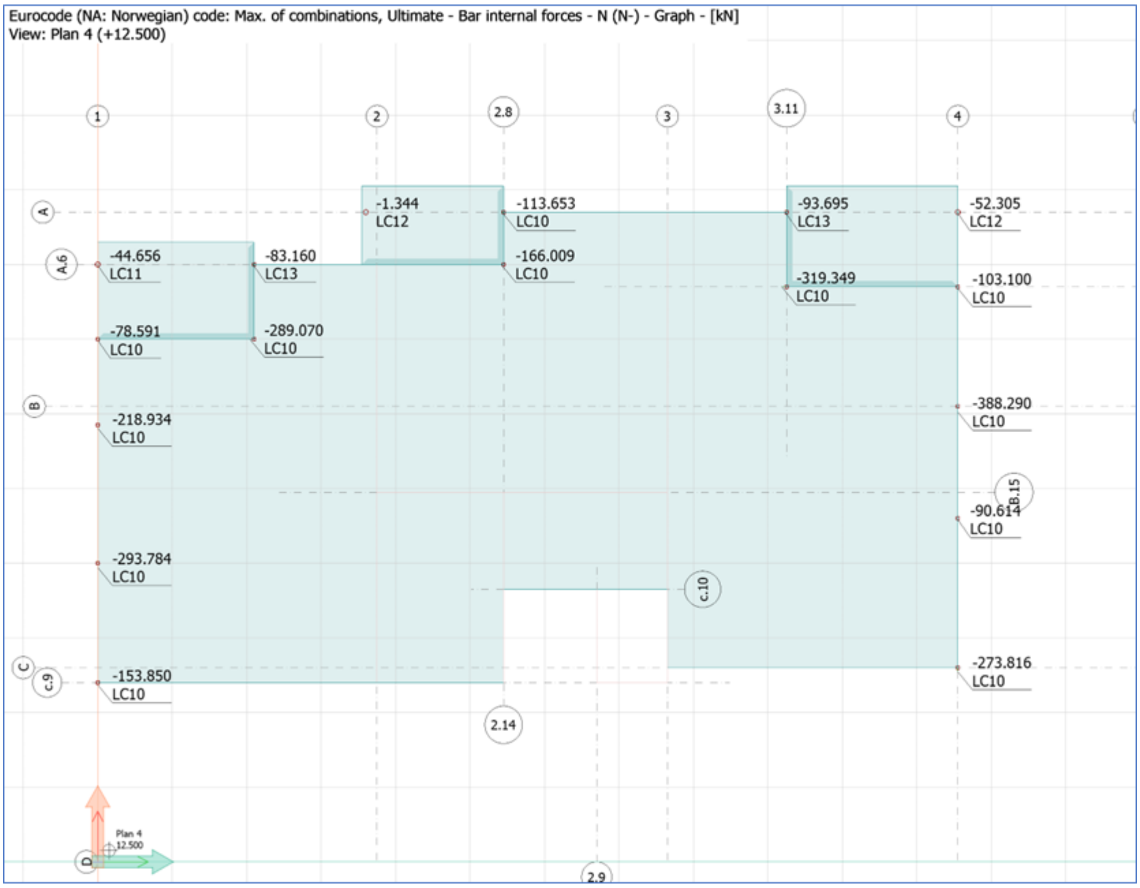

Figure A.5: Column loads, plan 04 in LG6

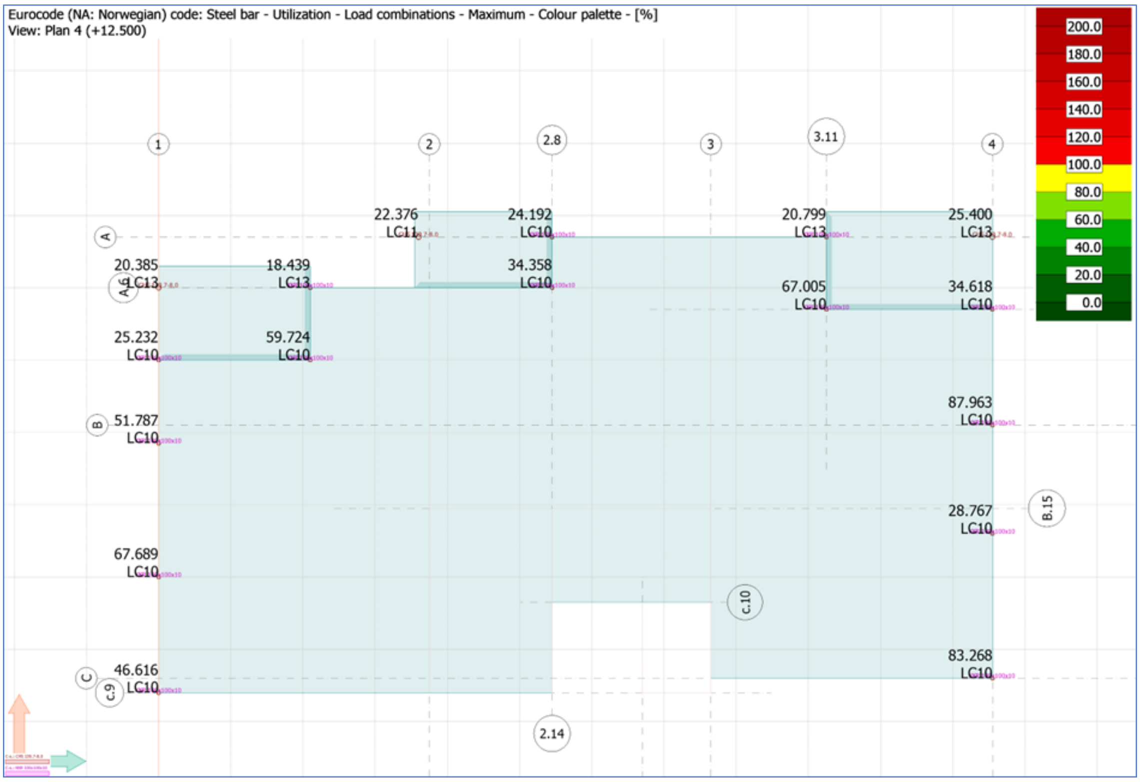

Figure A.6: Column utilization ratio in percent, plan 04 in LG6

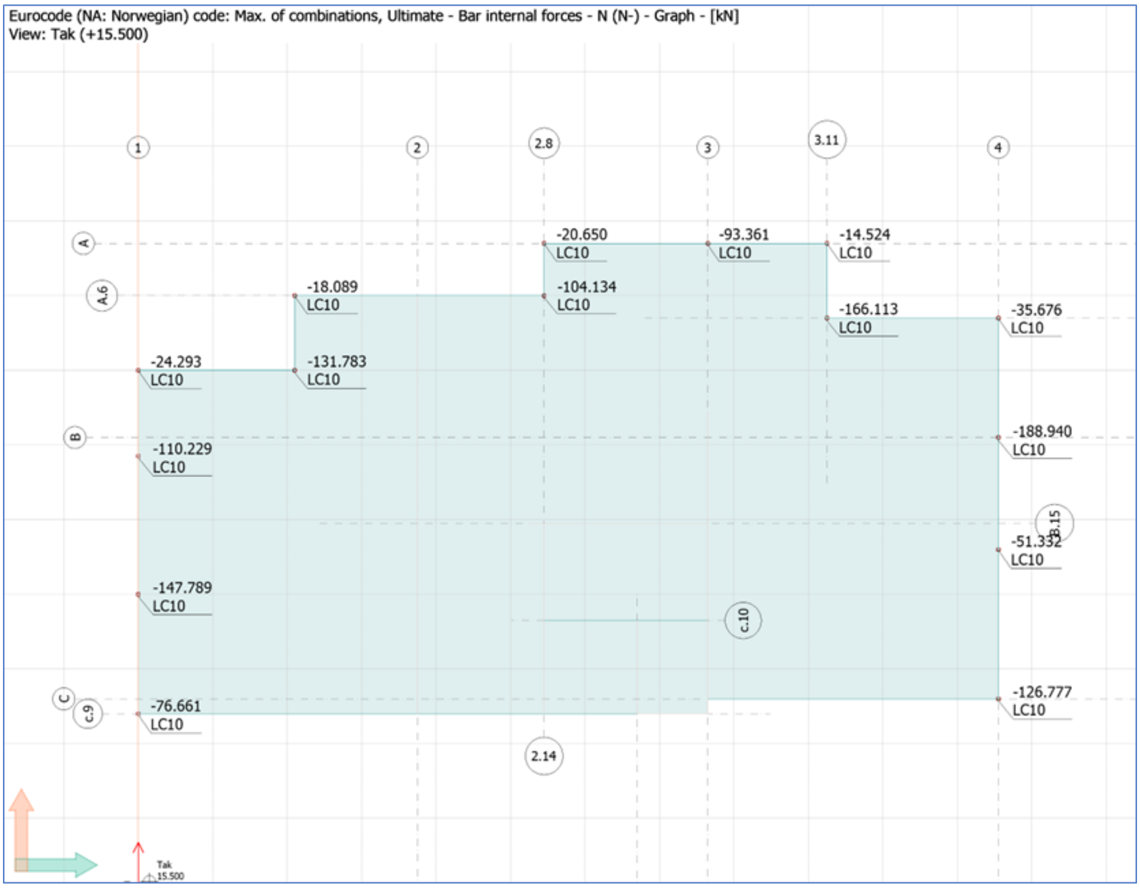

Figure A.7: Column loads, plan 05 in LG6

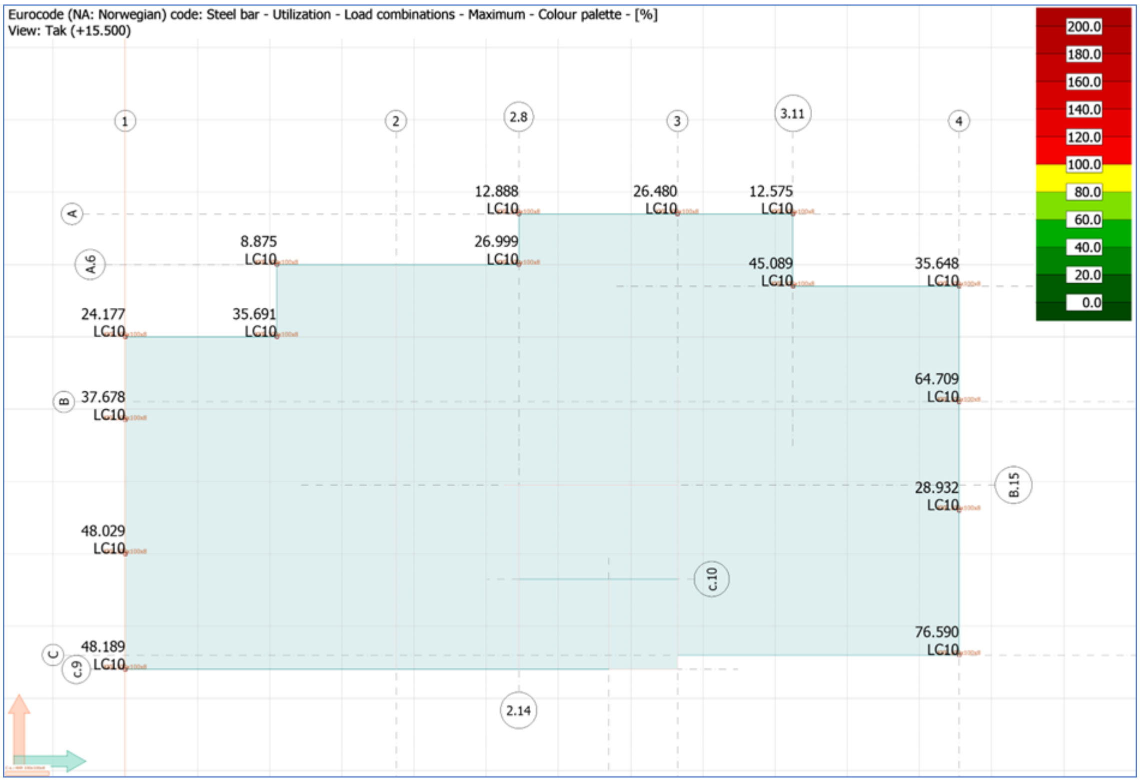

Figure A.8: Column utilization ratio in percent, plan 05 in LG6

Appendix B

B.1 Cross sections available for reuse

Table B.1: Geometric properties UC 305x305x97

UC 305x305x97			
Geometry			
Depth	h	307,9	mm
Width	b	305,3	mm
Web thickness	t_w	9,9	mm
Flange thickness	t_f	15,4	mm
Inner depth between flanges	h_i	277,1	mm
Root fillet radius	r_1	15,2	mm
Depth of straight portion of web	d	246,7	mm
Sectional area	A	123,4	cm^2
Bending			
Area moment of inertia about y-axis	I_y	22250	cm^4
Area moment of inertia about z-axis	I_z	7308	cm^4
Polar area moment of inertia	I_p	29558	cm^4
Radius of gyration about y-axis	i_y	134,2	mm
Radius of gyration about z-axis	i_z	76,9	mm
Polar radius of gyration	i_p	154,7	mm

Statical moment of area about y-axis	max S_y	796	cm^3
Statical moment of area about z-axis	max S_z	179,52	cm^3
Elastic section modulus about y-axis	W_y	1445	cm^3
Elastic section modulus about z-axis	W_z	478,7	cm^3
Plasticity			
Plastic section modulus about y-axis	$W_{pl,y}$	1592,23	cm^3
Plastic section modulus about z-axis	$W_{pl,z}$	726,15	cm^3
Plastic warping section modulus w.r.t. shear center	$W_{pl,\omega}$	10496,4	cm^4
Plastic shape factor about y-axis	$\alpha_{pl,y}$	1,102	–
Plastic shape factor about z-axis	$\alpha_{pl,z}$	1,517	–
Plastic shape factor w.r.t. shear center	$\alpha_{pl,\omega}$	1,5	–
Plastic shear area in y-direction	$A_{pl,y}$	94,03	cm^2
Plastic shear area in z-direction	$A_{pl,z}$	28,96	cm^2
Plastic limiting normal force	N_{pl}	2901,315	kN
Plastic limiting shear force in y-direction	$V_{pl,y}$	1275,806	kN
Plastic limiting shear force in z-direction	$V_{pl,z}$	392,888	kN
Plastic limiting bending moment about y-axis	$M_{pl,y}$	374,17	kNm
Plastic limiting bending moment about z-axis	$M_{pl,z}$	170,65	kNm

Table B.2: Geometric properties UC 356x406x235

UC 356x406x235			
Geometry			
Depth	h	381	mm
Width	b	394,8	mm
Web thickness	t_w	18,4	mm
Flange thickness	t_f	30,2	mm
Inner depth between flanges	h_i	320,6	mm
Root fillet radius	r_1	15,2	mm
Depth of straight portion of web	d	290,2	mm
Sectional area	A	299	cm^2
Bending			
Area moment of inertia about y-axis	I_y	79080	cm^4
Area moment of inertia about z-axis	I_z	30990	cm^4
Polar area moment of inertia	I_p	110070	cm^4
Radius of gyration about y-axis	i_y	162,5	mm
Radius of gyration about z-axis	i_z	2	mm
Polar radius of gyration	i_p	162,5	mm
Statical moment of area about y-axis	max S_y	2343,5	cm^3
Statical moment of area about z-axis	max S_z	587,94	cm^3
Elastic section modulus about y-axis	W_y	4151	cm^3
Elastic section modulus about z-axis	W_z	1570	cm^3
Plasticity			
Plastic section modulus about y-axis	$W_{pl,y}$	4686,68	cm^3
Plastic section modulus about z-axis	$W_{pl,z}$	2383,23	cm^3
Plastic warping section modulus w.r.t. shear center	$W_{pl,\omega}$	41282,01	cm^4
Plastic shape factor about y-axis	$\alpha_{pl,y}$	1,129	–
Plastic shape factor about z-axis	$\alpha_{pl,z}$	1,518	–

Plastic shape factor w.r.t. shear center	$\alpha_{pl,\omega}$	1,5	–
Plastic shear area in y-direction	$A_{pl,y}$	238,46	cm^2
Plastic shear area in z-direction	$A_{pl,z}$	64,55	cm^2
Plastic limiting normal force	N_{pl}	7036,946	kN
Plastic limiting shear force in y-direction	$V_{pl,y}$	3235,35	kN
Plastic limiting shear force in z-direction	$V_{pl,z}$	875,759	kN
Plastic limiting bending moment about y-axis	$M_{pl,y}$	1101,37	kNm
Plastic limiting bending moment about z-axis	$M_{pl,z}$	560,06	kNm

Table B.3: Geometric properties UC 356x406x287

UC 356x406x287			
Geometry			
Depth	h	393,6	mm
Width	b	399	mm
Web thickness	t_w	22,6	mm
Flange thickness	t_f	36,5	mm
Inner depth between flanges	h_i	320,6	mm
Root fillet radius	r_1	15,2	mm
Depth of straight portion of web	d	290,2	mm
Sectional area	A	367	cm^2
Bending			
Area moment of inertia about y-axis	I_y	99880	cm^4
Area moment of inertia about z-axis	I_z	38680	cm^4
Polar area moment of inertia	I_p	138560	cm^4
Radius of gyration about y-axis	i_y	165,3	mm
Radius of gyration about z-axis	i_z	2,8	mm
Polar radius of gyration	i_p	165,3	mm
Statical moment of area about y-axis	$\max S_y$	2906	cm^3
Statical moment of area about z-axis	$\max S_z$	725,44	cm^3
Elastic section modulus about y-axis	W_y	5075	cm^3
Elastic section modulus about z-axis	W_z	1939	cm^3
Plasticity			
Plastic section modulus about y-axis	$W_{pl,y}$	5812,66	cm^3
Plastic section modulus about z-axis	$W_{pl,z}$	2949,27	cm^3
Plastic warping section modulus w.r.t. shear center	$W_{pl,\omega}$	51876,24	cm^4
Plastic shape factor about y-axis	$\alpha_{pl,y}$	1,145	–
Plastic shape factor about z-axis	$\alpha_{pl,z}$	1,521	–

Plastic shape factor w.r.t. shear center	$\alpha_{pl,\omega}$	1,5	–
Plastic shear area in y-direction	$A_{pl,y}$	291,27	cm^2
Plastic shear area in z-direction	$A_{pl,z}$	80,7	cm^2
Plastic limiting normal force	N_{pl}	8594,432	kN
Plastic limiting shear force in y-direction	$V_{pl,y}$	3951,873	kN
Plastic limiting shear force in z-direction	$V_{pl,z}$	1094,978	kN
Plastic limiting bending moment about y-axis	$M_{pl,y}$	1365,97	kNm
Plastic limiting bending moment about z-axis	$M_{pl,z}$	693,08	kNm

Table B.4: Geometric properties UC 356x406x393

UC 356x406x393			
Geometry			
Depth	h	419	mm
Width	b	407	mm
Web thickness	t_w	30,6	mm
Flange thickness	t_f	49,2	mm
Inner depth between flanges	h_i	320,6	mm
Root fillet radius	r_1	15,2	mm
Depth of straight portion of web	d	290,2	mm
Sectional area	A	500,6	cm^2
Bending			
Area moment of inertia about y-axis	I_y	146600	cm^4
Area moment of inertia about z-axis	I_z	55370	cm^4
Polar area moment of inertia	I_p	201970	cm^4
Radius of gyration about y-axis	i_y	171,1	mm
Radius of gyration about z-axis	i_z	5,2	mm
Polar radius of gyration	i_p	171,2	mm
Statical moment of area about y-axis	max S_y	4111	cm^3
Statical moment of area about z-axis	max S_z	1016,31	cm^3
Elastic section modulus about y-axis	W_y	6998	cm^3
Elastic section modulus about z-axis	W_z	2721	cm^3
Plasticity			
Plastic section modulus about y-axis	$W_{pl,y}$	8222,62	cm^3
Plastic section modulus about z-axis	$W_{pl,z}$	4153,72	cm^3
Plastic warping section modulus w.r.t. shear center	$W_{pl,\omega}$	75346,11	cm^4
Plastic shape factor about y-axis	$\alpha_{pl,y}$	1,175	–
Plastic shape factor about z-axis	$\alpha_{pl,z}$	1,527	–

Plastic shape factor w.r.t. shear center	$\alpha_{pl,\omega}$	1,5	–
Plastic shear area in y-direction	$A_{pl,y}$	400,49	cm^2
Plastic shear area in z-direction	$A_{pl,z}$	113,16	cm^2
Plastic limiting normal force	N_{pl}	11763,783	kN
Plastic limiting shear force in y-direction	$V_{pl,y}$	5433,714	kN
Plastic limiting shear force in z-direction	$V_{pl,z}$	1535,308	kN
Plastic limiting bending moment about y-axis	$M_{pl,y}$	1932,32	kNm
Plastic limiting bending moment about z-axis	$M_{pl,z}$	976,13	kNm