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MASTER THESIS

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Structural Integrity Management ensuring robustness and barriers

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Summary

Offshore structures operate for decades in harsh environment. They are exposed to extreme environmental loads and degradation effects. Changes in configuration, weights and operational condition represent also a challenge. Lost knowledge and experience over time due to personnel leaving companies, unregistered or unmitigated changes, suboptimal inspection procedures and schedules may affect cost effective and safe operation.

Structural Integrity Management (SIM) is the process to ensure compliance with regulatory and company requirements over time, and thus ensure the structure is fit-for-purpose until decommissioning or removal. The SIM process involves systematic filing of all important historical information for later easy retrieval. This information relates to fabrication, structural assessments, inspection findings, modification or life-extension projects. It also forms a framework for scheduled and unscheduled inspections.

Barriers are used in the risk analysis and risk management regimes of socio-technical systems in order to help tackling the problems and diversities connected to accidents in a systematic way. Barriers are intentionally planned functions to prevent, control or mitigate the propagation of a hazardous event from making harm or reach its full consequences. It is common to have a series of barriers, each implementing a particular function, the serial sum of which is intended to cover all the foreseeable failure scenarios connected to the hazard.

Robustness is desirable property in structures and systems. Robustness is the quality that defines how structures behave outside their operational envelope and their potential to survive accidents. From a strictly structural point of view, robustness mitigates the susceptibility of progressive collapse, i.e. no damage disproportionate to the initial failure should occur. If robustness is defined with the use of barriers, it means such a layered defense system that is aimed to prevent initial damage and to hinder hazards from propagation, hence limit the consequences on humans, the environment and assets.

In the thesis it is shown that the purpose of SIM – ensuring suitability and safety – requires the SIM standards to incorporate and put emphasis on robustness and barriers.

SIMS, the software product of DNV GL is also presented in the thesis. SIMS is a supporting tool for Structural Integrity Management processes that was created to be a change management database. SIMS integrates the Survey changes, Assess changes, Find information and Ensure integrity functions. SIMS is able to handle a large portfolio of platforms in a resource effective way, with adequate care to information security. The aim of SIMS is integrity assurance which is achieved by barrier control with full compliance to NORSOK standards.

To demonstrate numerical calculations in connection with structural robustness, a member consequence calculation of an offshore bridge with truss girders is performed.

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I would also like to thank Michael Hall (ConocoPhillips Norway) who granted me access to many valuable sources of information as well as agreed that I could use the SIMS software in this semester and I can include it in my thesis.

In connection with the SIMS software and other topics of the thesis, I also feel grateful for many colleagues and friends at DNV GL who gave suggestions, opinions, and answers to my questions.

I also feel obliged to InterCad Ltd, who provided access to the full version of their structural engineering analysis software AxisVM free of charge for the time of this thesis.

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15 June 2015

István Szarka

1 Introduction

1.1 Objective of the thesis

The thesis is organized around the topics of Structural Integrity Management (SIM), barriers and robustness. The objective of this thesis is:

- to investigate and evaluate what role SIM has in structural safety,
- to find out what methods and activities SIM involves to achieve its goals
- to find similarities in and differences between standards that describe a SIM process (API, ISO, NORSOK)
- to see if the methods and principles currently incorporated in SIM standards can fulfill their goal
- to introduce and critically evaluate an example of a software database tool that supports the SIM process (DNV GL's SIMS)
- to study what kind of connection there is between SIM and barrier concept, to examine if current SIM standards include barrier philosophy
- to look at what is robustness and how it is connected to barriers or SIM, also to see if current SIM standards set focus on robustness and if these should do that

In addition, it is also the aim of this thesis to provide an example of numerical calculations in connection with robustness and member consequence.

1.2 Limitations of the thesis

The management and assessment of structural integrity for existing offshore loadbearing structures is a very broad topic. This thesis is limited to fixed offshore structures which have their activities in connection with the oil industry.

Regarding the topics in connection with Structural Integrity Management standards, the focus is on their scope, objective and general principles, management considerations and general integrity management process descriptions. The specific regulations for topsides, jackets, concrete, column stabilized, ship-shaped or other specific structures, as well as marine systems are not within the scope of this thesis

The set up or necessary technical means of inspection programmes, inspection methods; methods of damage evaluation and specific methods of assessment of fatigue loading, seismic loading, ice loading, etc.; as well as platform decommissioning is also not within scope.

1.3 Abbreviations used in the thesis

The following abbreviations are used in the text:

AAc	As-is assurance compliance (DNV GL SIMS)
AAm	As-is assurance model (DNV GL SIMS)
AASAS	As-is Structure Analysis Summary (DNV GL SIMS)
ACT	Analysis Change Task Summary (DNV GL SIMS)
ALS	Accidental limit state
API	American Petroleum Institute
ASIS	As-is Structure Integrity Summary (DNV GL SIMS)
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
FLS	Fatigue limit state
FMD	Flooded member detection
GBS	Gravity based structure (DNV GL SIMS)
GEA	Greater Ekofisk Area
GPS	Global Positioning System
HSE	Health Safety and Environment
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LRFD	Load and Resistance Factor Design
MSS	Module support structure (DNV GL SIMS)
NCS	Norwegian Continental Shelf
NORSOK	The NORSOK standards (Norsk sokkels konkurranseposisjon)
PSA	Petroleum Safety Authority Norway (Petroleumtilsynet)
RBI	Risk Based Inspection
RSR	Reserve Strength Ratio
RP	Recommended practice

SAS	Structure Analysis Summary (DNV GL SIMS)
SCA	Structure Condition Anomaly (DNV GL SIMS)
SIM	Structural Integrity Management (in service)
SIMS	Structural Integrity Management System (product of DNV GL Software)
SIMS-a	SIMS Analysis Portal (DNV GL SIMS)
SIMS-e	SIMS Ensure Portal (DNV GL SIMS)
SIMS-f	SIMS Find Portal (DNV GL SIMS)
SIMS-s	SIMS Survey Portal (DNV GL SIMS)
ULS	Ultimate limit state
WSD	Working Stress Design

2 Structural Integrity Management

2.1 Introduction

The following chapters are aimed to describe how the definition and the process of Structural Integrity Management (SIM) are defined in the relevant codes and regulations. First the recommended practice for structural integrity management (API RP2SIM) from the American Petroleum Institute /1/ together with the International Standard 19902 from ISO /2/ in section 2.2 is the subject of investigation, afterwards the NORSOK N-005 standard /3/ together with NORSOK N-006 /4/ in section 2.3. Finally DNV GL's SIM software, which supports the SIM process is introduced.

Structural integrity management is a cyclic process that has been created to ensure that structures can maintain their integrity and their prescribed safety level. Structural inspections, assessment and maintenance are the focus points of SIM. The enabling factor to the SIM activities is the informed decision and change management that take up-to-date and transferable data as a basis.

With the use of SIM one can prioritize inspection resources, classify structures and components on the basis of strength, risk, criticality, fatigue characteristics, reliability and consequence of its failure. The SIM process enables the operator to get an increased knowledge of structural assets and their properties, as well as ensures that personnel with the adequate qualifications make assessment of these assets, if necessary by the means of updated structural analysis models.

Although SIM is not part of the design process, it is a cradle to grave activity in the structure's lifetime /5/ that has been brought to life by the need to tackle the challenges connected to structure aging and deterioration processes, complex and extensive modification and life extension projects, as well as assure safe decommissioning.

2.2 SIM using API RP2SIM /1/ and ISO19902 /2/

2.2.1 General

The reason for API RP2SIM /1/ and ISO19902 /2/ are addressed in a shared section is that the two standards have very much in common when it comes to definitions and concepts of platform failure consequence, categorization of inspections and structural integrity management in general. The main focus is on API RP2SIM since in that case, the whole document is devoted to structural integrity management.

The scope of the API RP2SIM is for fixed offshore structures built and used by the petroleum industries. The processes could be applicable for structures located anywhere in the world, but some specific guidance and criteria limit the practical use for the Gulf of Mexico. The SIM process itself defined in the RP can be used in connection with any type of structure. The API RP2SIM was written with the intention to give guidance for platforms designed with a working stress design (WSD) approach, but the framework is general enough to be used with a load and resistance factor design (LRFD) method.

In this thesis the focus is on Section 4 (Structural Integrity Management Process) of the API RP2SIM. That is the main chapter of the recommended practice. The other chapters in the RP deal with detailing and providing guidance on a particular SIM task.

ISO19902 has a very similar scope, namely it defines “in-service inspection requirements for both the underwater and above water parts of fixed steel offshore structures located anywhere in the world, built to any design and fabrication standard, and of any age” /2, section 23.1.1/. In the case of ISO19902 our focus is mainly limited to chapters 23, 24 and their annexes (A.23, A.24).

2.2.2 Definition of SIM used in API RP2SIM and ISO19902

Section 1.1 in API RP2SIM defines the SIM process as “SIM is a continuous process used for demonstrating the fitness-for-purpose of an offshore structure from installation through to decommissioning. SIM provides the process for understanding the effects of deterioration, damage, changes in loading and accidental overloading. In addition SIM provides a framework for inspection planning, maintenance, and repair of a platform or group of platforms. The SIM process (...) consists of four primary elements: data, evaluation, strategy, and program.”. The process of SIM described is generic, stepwise and cyclic. The SIM process is a tool for the operator to predict the performance of the structure in ill conditions (damaged, overloaded), by a set of techniques which include analysis, testing and monitoring. The hence understood structural behavior provides the basis for a tailored inspection program for the entire life of the platform. Furthermore SIM provides input to decision makings on platform future (e.g. life extension, modifications, eventual removal).

ISO19902 describes SIM as a structured method to assure the condition of the structure in a cyclic activity that deals with data collection and evaluation, development of an inspection strategy, development and execution of an inspection program, and execution of repairing works. ISO19902 defines the possible benefits of a SIM program as:

- inspection resources are better utilized because structural elements on system or component level can be prioritized on the basis of strength, risk, criticality or reliability
- becoming more knowledgeable on the structure through the review of data and assessments by qualified personnel
- change management becoming effective: storing, reviewing, evaluating of data enables better assessment of consequences
- SIM enables planning both for repairs and inspections.

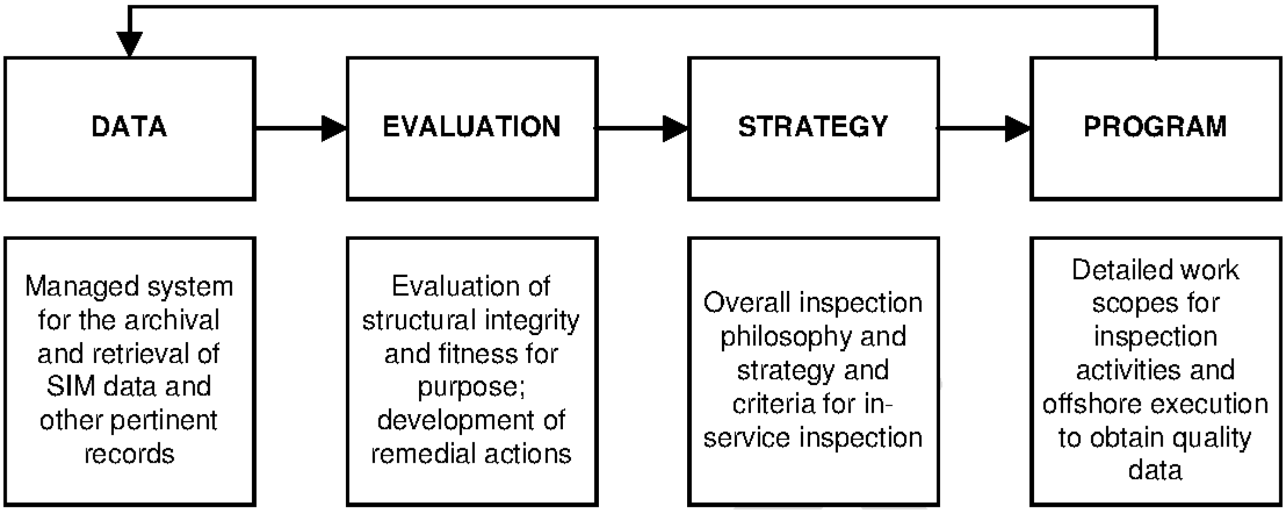


Figure 2.1 The four stages of the SIM process in API RP2SIM and ISO19902, based on /1/

2.2.3 Risk based approach of API RP2SIM

The overall strategy of API RP2SIM, when it comes to inspection criteria, is that it defines a inspection scope and minimum frequency based on qualitative evaluations, however it is possible to justify reduced criteria with quantitative methods.

The SIM process can provide means to apply a risk based approach in operating platforms. Risk is defined in the API RP2SIM as:

$$\text{Risk} = \text{Likelihood x Consequence}$$

Likelihood: by likelihood, it is meant likelihood of failure of the platform. It is (e.g.) the conditional probability of a hurricane being of a great enough magnitude to damage the platform given there is a hurricane in the platform area.

$$P(A|B)=\frac{P(A\cap B)}{P(B)}$$

Consequence: the consequence is the loss due to the platform failure that either can or cannot be measured in terms of economic loss. This is the loss of life, pollution, repairs, lost production, unexploited hydrocarbon reserves.

The goal of the risk based approach utilized by the API RP2SIM is that higher risk platforms may have surveys and inspections more frequently as well as the scope and extent of the survey is broader than for low risk platforms. I.e. the cost of inspections is proportional to the risk that operating the particular platform poses.

2.2.4 Elements of the SIM loop

The Figure 2.1, which shows the four main elements of the SIM process, can be found in API RP2SIM (Figure 1) and in almost similar form in ISO19902 (Figure 23.1.1). It has to be noted, however that ISO19902 makes a little addition to this figure by introducing the Design element which provides input to the Data block, hence it emphasizes that the SIM loop represents an in-service / operation phase. As it was mentioned earlier, and can be seen in Figure 2.1, the SIM process is cyclic and continuous. This figure represents a concept that information is fed back to the data block after inspection. That is, it is the inspection findings that bring a new element to the SIM cycle at the next iteration.

2.2.4.1 Data

The SIM process relies on correct, accurate and up-to-date information. Correct data is critical in SIM. Inaccuracy or lack of information can lead to unsafe operation, conservative decisions, that may prevent better use or modification of the platform.

Data covers all information from design, fabrication, installation and operation. The type of data can be reports, analyses, results of inspections, metocean information. The stored data hence must cover:

- reports and eventually models from all original design analyses and re-analyses in the operation phase as well as analyses that document modifications
- inspection data from fabrication, transportation, installation and in-service phases
- any kind of structural modification, weight changes, strengthening, records if any of the other design parameters have changed (e.g. environmental)
- incidents, repairs, damage history.

It is important that in case of an owner change, all data is transferred to the new owner. The API RP2SIM splits the stored data in two categories:

- characteristic data, which describe the as-installed condition of the platform
- condition data, which contains records on any kind of change that is of concern in connection with the platform, but also records on surveys for corrosion or protection systems even if the result was no finding.

It is possible to gain data on structural condition not only with inspections but with monitoring systems also. These systems enable the continuous monitoring of structural response characteristics. Changes of such response characteristics can indicate degradation of structural performance (development of cracks, foundation stiffness reduction due to scour, mass distribution changes on the deck)

2.2.4.2 Evaluation

Evaluation is the process where the engineer(s) decide on the relevance and importance of new and existing data using their competence. API RP2SIM and ISO19902 make a distinction between evaluation and assessment. In Figure 2.2 evaluation and assessment is shown in the same figure (which is otherwise very similar to Figure 2.1). In ISO19902 there is a detailed comparison between evaluation and assessment. The distinction between the two can be formulated as:

- Evaluation is an ongoing process and there are many forms of it. Engineering competence is needed to decide on whether engineer judgment (experience of specialist knowledge) or a detailed structural analysis is needed. There are also options between the above two extremes. E.g. comparing to similar platforms, and their analyses.
- Evaluation can be performed right after receiving new data. For example if damage or deterioration is found it can be evaluated if this has direct consequence being on a primary member or not; as well as it can also be decided if the new data is not sufficient, hence if more inspection is required, and based on the member criticality when the new inspection will be required.
- Assessment is a triggered event and can only come from evaluation. Assessment is a detailed evaluation or a structural analysis

On the other hand, the two processes (evaluation and assessment) share most of the data necessary for performing them. The assessment process is further described in section 2.2.4.3.

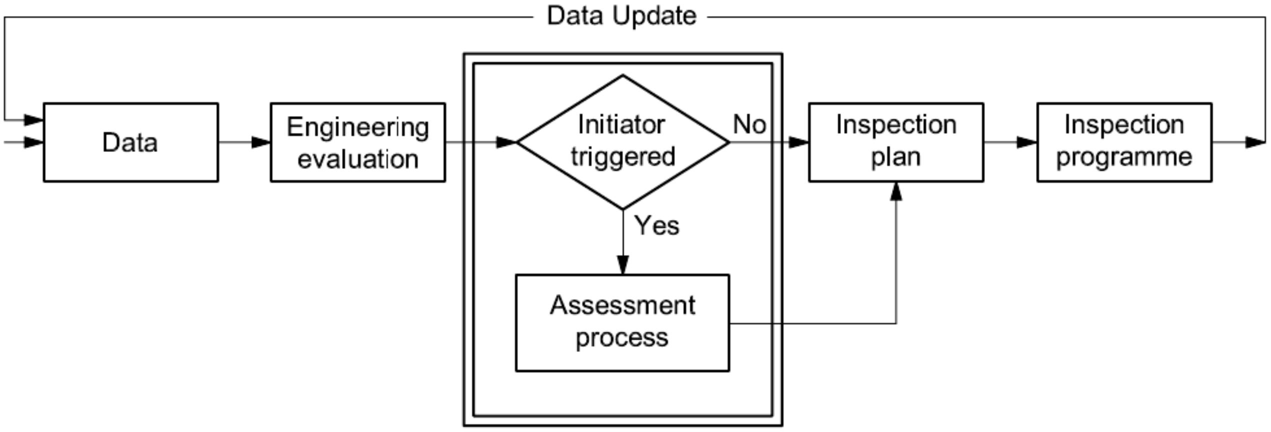


Figure 2.2: Assessment in the SIM process in API RP2SIM, source /1/

API RP2SIM lists a number of factors that are to be considered when the evaluation is made: “

a) platform age, condition, original design criteria

b) analysis results and assumptions for original design or subsequent assessment

c) platform reserve strength and degree of structural redundancy

d) degree of conservatism or uncertainty in metocean criteria

e) fabrication quality and occurrence of any rework or re-welding

f) occurrence of any damage during transportation or installation

g) extent of inspection during fabrication, transportation and installation

h) in-service inspection findings (physical)

i) learning from other similar platforms

j) platform modifications, additions and repairs or strengthening

k) accidental (i.e., fire, blast, vessel impact, dropped object, etc.) or metocean or other design event overload

l) fatigue sensitivity

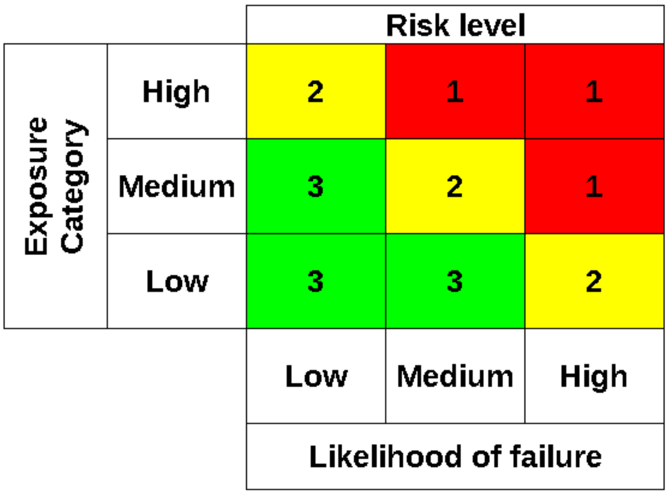
m) past performance of corrosion protection system

n) criticality of platform to other operations

o) platform monitoring data" /1/

Very similar factors and issues to be considered can be found in ISO19902. These are listed in Appendix A.

The API RP2SIM provides the possibility for the operator to utilize a risk based SIM strategy. As it is mentioned in section 2.2.3, risk is defined as the product of likelihood and consequence. In API RP2SIM, consequence is represented as "Exposure category".



Exposure Category	Risk level: Low	Risk level: Medium	Risk level: High
High	2	1	1
Medium	3	2	1
Low	3	3	2
	Low	Medium	High
	Likelihood of failure		

Figure 2.3: Risk matrix in API RP2SIM, based on /1/

Figure 2.3 shows the basis of risk based strategy used in API RP2SIM. The goal of the risk matrix is to communicate the severity of the evaluation results. The recommended practice makes the following categories of platform based on risk exposure: "

a) Risk Level 1 — Platforms that reside in this risk category should be considered for a major focus of resources, which may include an increased inspection frequency and intensity of inspection and/or more detailed engineering.

b) Risk Level 2 — Platforms that reside in this risk category may be considered for a moderate focus of resources.

c) Risk Level 3 — Platforms that reside in this risk category may be considered for less focus of resources, which may include a reduced inspection frequency and scope of inspection." /1/

There are two factors in API RP2SIM that define exposure category:

- *life-safety* and
- environmental exposure/economic impact (which is named *consequence category*).

Life-safety describes how much the platform is manned in the event of the maximum anticipated environmental event:

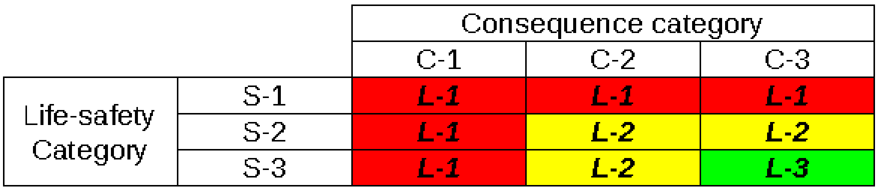
- S-1: manned, non-evacuated: the platform is (almost) continuously manned, personnel will not be evacuated
- S-2: manned, evacuated: the platform is (almost) continuously manned, except for when there is a forecast extreme environmental event. The requirements for a platform to be categorized as S-2 are that there should be enough resources to carry out the evacuation; there has to be a plan on evacuation prior to the extreme environmental event; in case of the forecast event, there is sufficient time to evacuate personnel.
- S-3: unmanned: normally not manned platforms. Platforms that have living quarters cannot be in this category.

Consequence categories describe the extent of possible environmental damage and cost of the operator in case of platform failure:

- C-1: high consequence of failure: for major platforms where the danger of hydrocarbon leakage is present, either in the form of well leakage or major oil transport lines cross the platform
- C-2: medium consequence of failure: for platforms where oil and gas production is shut down in a design event, i.e. leakage is prevented.
- C-3: low consequence of failure: production is shut down in a design event, minimal oil storage limited to functionality needs.

In Figure 2.4 the combination of consequence category and life-safety categories are shown, from which the appropriate exposure category can be selected.

It can also be seen in Figure 2.4 that life-safety is an independent category within the consequence of failure. This results in that life-safety has an increased importance (e.g. the S-1 category sets exposure category to L-1, independently of consequence category).



		Consequence category		
		C-1	C-2	C-3
Life-safety Category	S-1	**L-1**	**L-1**	**L-1**
	S-2	**L-1**	**L-2**	**L-2**
	S-3	**L-1**	**L-2**	**L-3**

Figure 2.4: Exposure categories from Life-safety and Consequence, based on /1/

For the likelihood of failure in Figure 2.3, the API RP2SIM defines three categories. The likelihood of failure is proportionate to the reserve strength ratio (RSR), i.e. how much the forces from the extreme event could be scaled up so that the platform is still not failing globally.

The API RP2SIM gives the possibility to define the likelihood of failure either quantitatively, semi quantitatively or only qualitatively. The result of this evaluation puts the platform in one of the following three likelihood categories:

- high likelihood: RSR<1.0, i.e. it is likely that the platform will not survive the design event (100 year return period)
- medium likelihood: platforms that are neither low of high likelihood of failure. It is a requirement that they are not expected to fail in the design event
- low likelihood: these platforms are not to be damaged and are very unlikely to fail in a design event.

ISO19902 makes the same categorizations with respect to life-safety, consequence or exposure.

2.2.4.3 Assessment

As stated in section 2.2.4.2 assessment is a triggered event based on an evaluation. An assessment will often involve a numerical analysis where the purpose is to make a comparison between:

1. the calculated strength of the structure, or proof / overload
2. and the required performance criteria.

As it was discussed before, the start of the assessment process is triggered by the initiator event. This practically means that some change (e.g. inspection finding) was serious enough, and its consequence is great or uncertain enough to need a detailed, documented, quantitative comparison.

The result of assessment can be that the platform is fit-for-purpose or risk reducing measures have to be taken. The general process of assessment is presented in Figure 2.5.

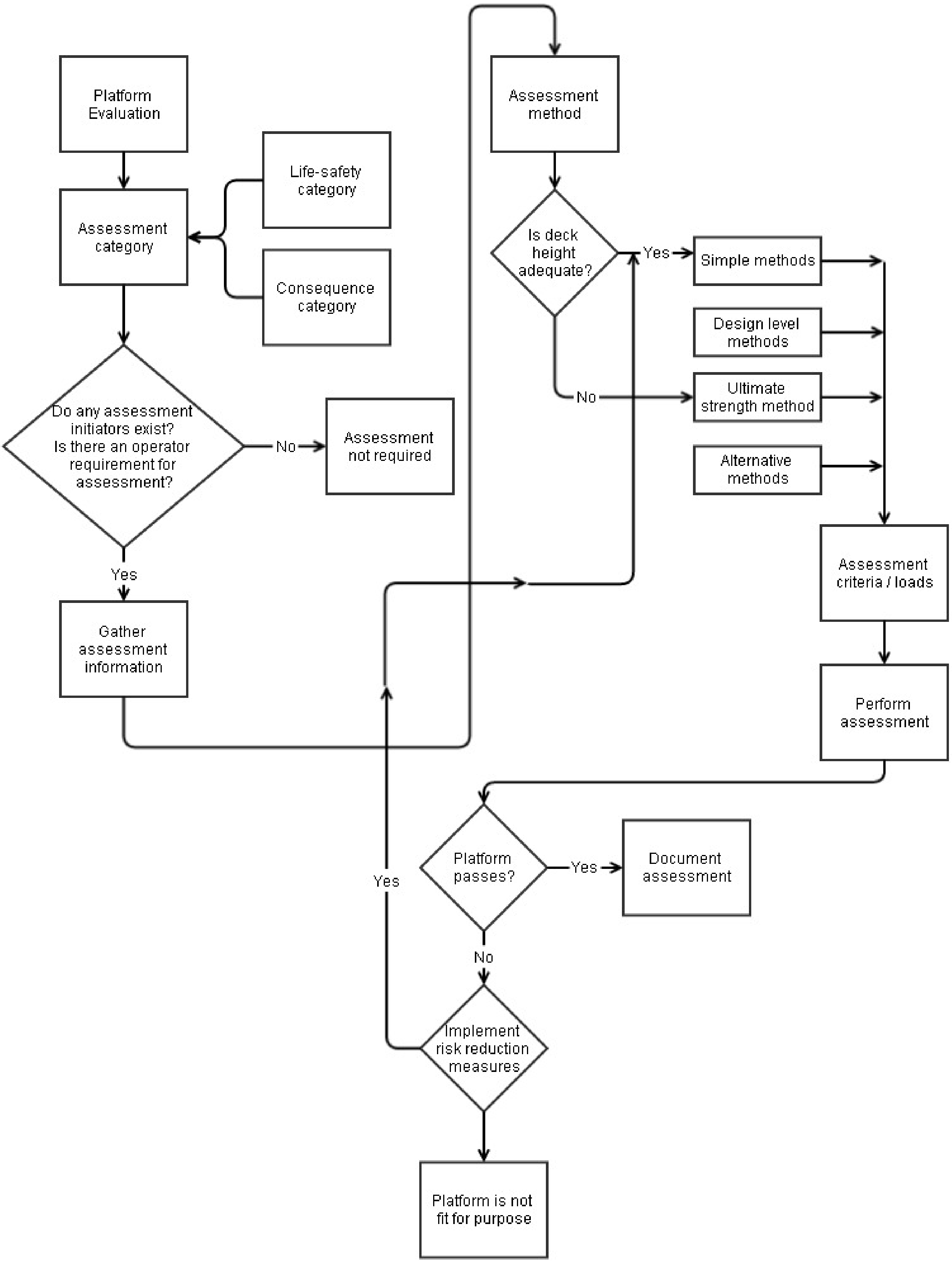


Figure 2.5: Assessing fitness-for-purpose, based on /1/

An assessment process is triggered if one or more of the following initiators happen:

- personnel added on the platform, hence the life-safety category changes
- there is an addition to the facilities on the platform which increases its consequence category
- if there is an increased loading on the structure. This can be environmental or operating. An assessment is triggered in case there is a 10% increase in the loading
- inadequate deck height, and the platform was not designed for wave impact
- there is a significant damage to the platform. A single or combined damage is to be considered significant if it reduces the structure's system capacity by at least 10%
- in case of increased cumulative loading and damage (if the combined effect is at least 10%)

In Figure 2.5 it can be seen that there are 4 different assessment method categories that the API RP2SIM distinguishes.

- Simple methods: using results from a previous analysis, comparison with similar platforms
- Design level method: it is a detailed analysis of the platform. Typically an elastic ULS or ALS code check to meet the design criteria in the platform's as-is condition
- Ultimate strength method: in contrast with the design level method which is a component check, this one focuses on the system capacity of the structure, hence it is often a non-linear analysis
- Alternative methods: There are two basic types, the method of historical performance and the explicit probabilities of survival. The first one can be used if the platform has been exposed to a certain load without significant damage before, and hence capacity can be documented this way. The second is a probabilistic analysis, where it is important to justify the probabilistic performance criteria to the deterministic assessment methods.

It is also clear from Figure 2.5 that API RP2SIM focuses on a ULS/ALS analysis when it refers to assessment.

The ISO19902 depicts the assessment process a little bit differently (Figure 2.6), but in its main concepts (focusing on capacity limit states) it is similar to API RP2SIM.

2.2.4.4 Strategy

The basis of strategy is the platform risk assessed with quantitative methods (Figure 2.3) or the qualitative exposure category. The two methods really make a difference when it comes to in-service routine underwater inspections. The approaches provided are: “a risk-based underwater survey (...) and an exposure-based underwater survey. When the owner/operator has not adopted a risk-based SIM strategy, an exposure-based (default) inspection program should be used.” /1/.

In general the API RP2SIM offers two options in connection with strategy:

- risk control, where the inspection plan should define the scope, frequency, methods, tools/techniques of the inspections
- risk mitigation, where the risk reduction methods are either improving on the consequence or the likelihood side as described in section 2.2.4.2

The inspection plan defines when and how the inspections are carried out, but is less detailed, and is not a work instruction as the inspection program (see section 2.2.4.5). The inspection plan is/should be updated on a regular basis, based on the data stored and evaluated in the SIM system. There are two topics in connection with inspection plans that the API RP2SIM discusses, which are the scope of the inspections and the strategy in connection with the inspections.

Inspections should be carried out:

- regularly for the above water parts of the structure
- for the under water parts:
    1. to assess as-installed condition a baseline inspection, so that it can become a basis of later inspections and SIM evaluation. This baseline inspection will also become an input to any risk based inspection program. The minimum scope of work for this inspection should include:
        a) “a visual survey of the platform for structural damage, from the mudline to top of jacket, including coating integrity through the splash zone
        b) a visual survey to verify the presence and condition of the anodes
        c) a visual survey to confirm the presence and condition of installed appurtenances
        d) measurement of the as-installed mean water surface elevation, with appropriate correction for tide and sea state conditions
        e) record the as-installed platform orientation
        f) measurement of the as-installed platform level”
    2. regular under water inspections (see Inspection strategy below)
- non scheduled inspections that are to be carried out after a storm or collision

In terms of a general and high level inspection strategy the API RP2SIM accepts two approaches:

- The structure is designed to be robust and high calculated fatigue lives are achieved in the design process. This way it is possible to reduce operating costs with respect to inspections.
- The strategy is based on an early detection of damage or corrosion and prompt inexpensive

repairs. This is applicable if the structure is deemed less robust, hence minor defects can compromise to a great extent the system capacity.

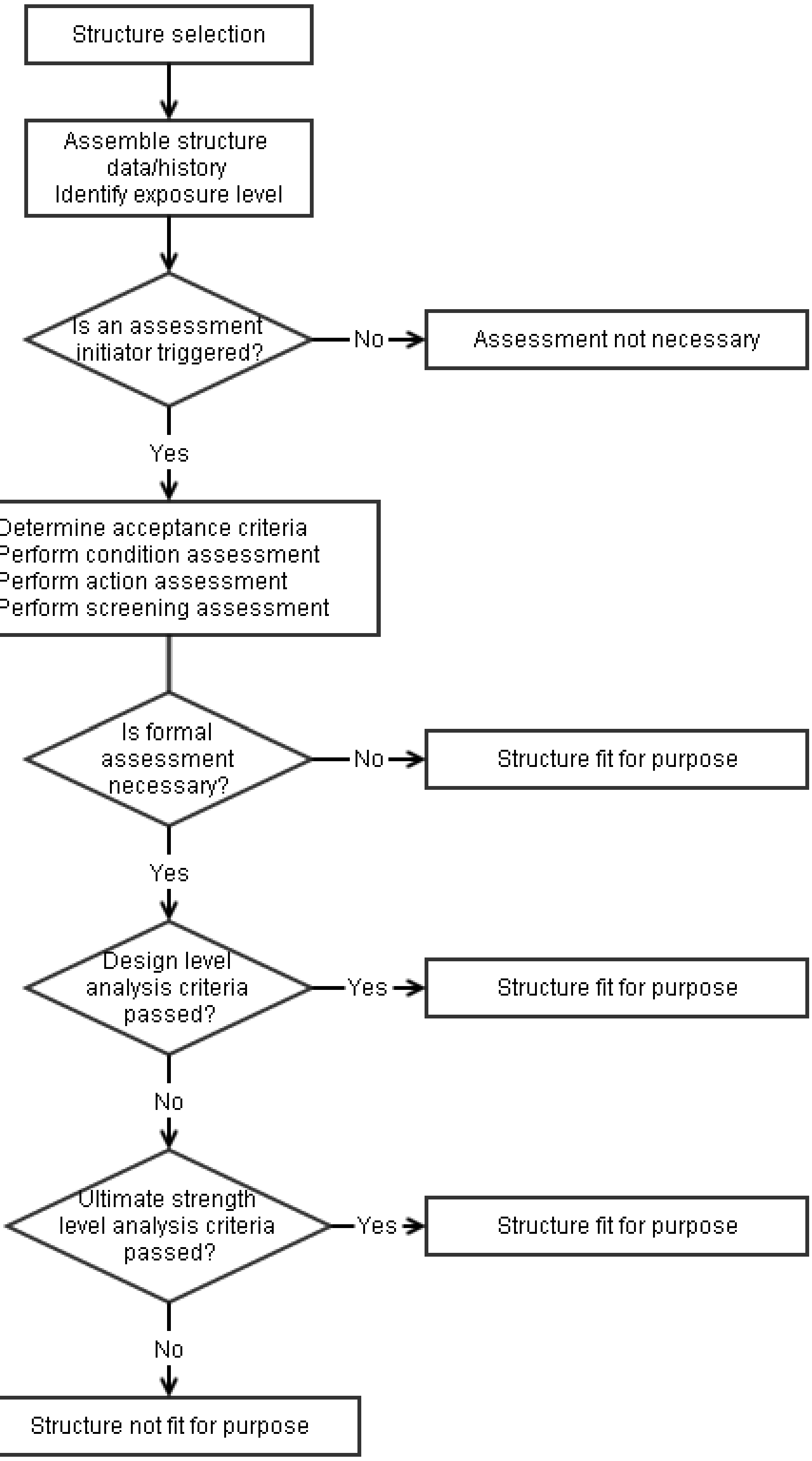


Figure 2.6: Assessment process, based on /2/

Within strategy, it is possible to talk about risk reduction that happens within the limits of the risk evaluation regime. It is possible to use exposure mitigating measures that reduce the consequence of failure. These measures include:

- improving life-safety category: making plans for evacuating personnel before the design event, reducing permanently the number of personnel
- improving consequence category:
    1. preventing hydrocarbon leakage by:
        a) installing sub-surface safety valves
        b) permanently or temporarily close down wells
        c) reducing/removing the stored hydrocarbon amount
        d) isolating pipelines
    2. removing / re-routing major oil lines, gas flow lines

It is also possible to make improvements on the other side of the risk matrix, namely to reduce the likelihood of structural failure by the following measures:

- removing damaged parts and components (member and crack removal)
- reducing loads (dead weights, marine growth removal, deck raising, taking shielding effects into account)
- localized and global strengthening (member-, joint- and leg-pile grouting, additional braces with clamps)

2.2.4.5 Program

The Program block in a SIM process represents the actual inspection scope, schedules, assigned personnel, budget and prescription of methods. It may refer to any of the inspections mentioned in the Strategy part (baseline, routine, special, etc.). The program itself is developed from the inspection strategy.

2.3 SIM in NORSOK N-005 /3/ and NORSOK N-006 /4/

2.3.1 General

The foreword of NORSOK N001 states that NORSOK standards are usually based on international standards. They are developed by the Norwegian petroleum industry to “ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations” /3/. It is the intention NORSOK standards to replace oil company specifications where possible.

In this section it is NORSOK N-005 /3/ and NORSOK N-006 /4/ which is being dealt with. Both of them serve as a supplement to NORSOK N-001 /6/ which is the principle standard for offshore structures.

The purpose of NORSOK N-005 is to cover all aspects of integrity management for all types of offshore loadbearing structures “including substructures, topside structures, vessel hulls, foundations, mooring systems and marine systems such as water and weather tight systems, stability systems and station keeping systems” /3/.

NORSOK N-006 details the general principles, guidelines and requirements that are needed for the assessment of structural integrity of offshore structures in-service and before life extension. In addition to being a supplement to NORSOK N-001, the Scope section of NORSOK N-006 states that N-006 “serves as an alternative of the N-001” /4/ standard in case a structure, that is to be assessed, will be operated beyond its lifetime, original design requirements, and it is difficulty possible to document code compliance. In these cases N-006 provides methods to use information gained during the life of the structure to demonstrate adequate strength.

NORSOK N-005 is used for the structural integrity management parts of this section, while N-006 is used for the assessment parts.

2.3.2 Using a draft edition of NORSOK N-005

At the time of writing this thesis, the Rev 1 version of the NORSOK N-005 /7/ is the valid document. However, a new and updated version of NORSOK N-005 /3/ is being prepared, which is used as source in this thesis. Unless noted otherwise, all references to NORSOK N-005 refer to /3/. The used version of NORSOK N-005 is an unfinished, living document, hence later changes can be expected, however it is expected that there will be no new draft revision before the completion of this thesis.

The purpose of the update was to cover the whole integrity management process (plan, survey, assess, adjust) as well as to include marine systems in NORSOK N-005. This way NORSOK N-005 can provide a broad scope on risks, hazards, preparation, response and performance of integrity management. In addition it defines its scope as “principles, practices, functional requirements and guidelines for the integrity management of structural and marine systems throughout their lifetime, including decommissioning and final removal” /3/.

2.3.3 Description of integrity management in NORSOK N-005

It is worth noting in advance, that N-005 uses surveillance for what API RP2SIM /1/ and ISO19902 /2/ used inspection. It has to be noted however that in NORSOK N-005 surveillance is defined with a broader meaning than the physical inspection of structures only: “The in-service activity concerned with detecting changes to the design regime, configuration and design actions for integrity assessments.” /3, section 3.1.31/. I.e. documents can be a subject to surveillance. This is also because data is input to evaluation and assessment and the data covered here is much more than inspection data of the structure.

The N-005 has a complex picture on integrity management (see Figure 2.7). The four main blocks of API RP2SIM that can be seen in Figure 2.2 can also be found in the “As-is surveillance” box, but the figure is very much extended from the one found in API RP2SIM or ISO19902.

In Figure 2.7:

- solid lines indicate continuous activities (e.g. the cyclic process inside the "As-is surveillance" box)
- dashed lines with a narrow gap (╍╍╍) indicate improvement and quality assurance activities (starting from Integrity assessment, getting input from Compensating measures and providing input to Integrity management strategy)
- dashed lines with a wide gap (— — —) indicate Integrity management strategy improvements (taking As-is surveillance as a starting point). This represents the intention of continuous improvement.

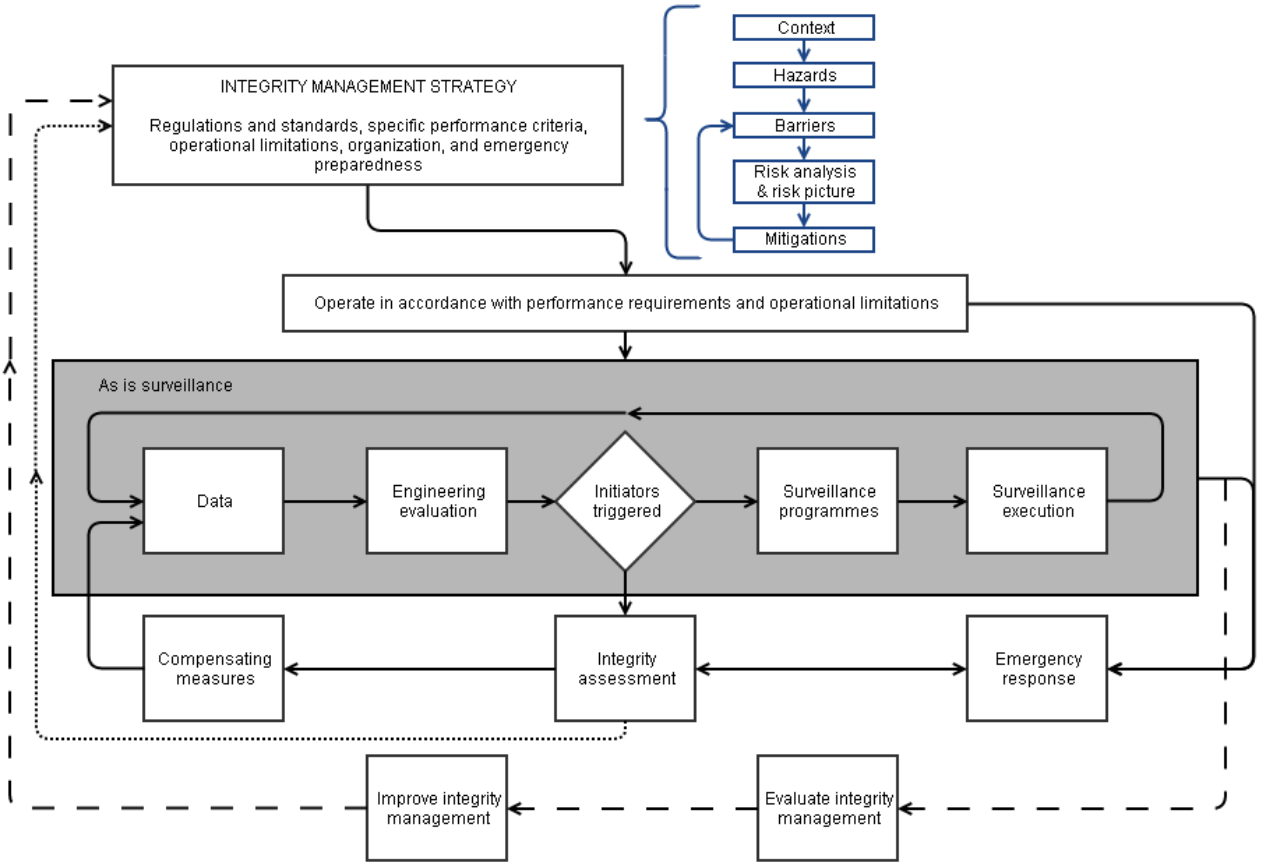


Figure 2.7: Integrity management process, based on /3/

According to N-005, barrier management is part of the Integrity management strategy, and it is defined as having strategies for protecting a facility against hazards, by means of barriers with a specific function that either block hazards or reduce the consequences of hazards. Integrity management shall incorporate strategies to maintain and review barriers, monitor barrier performance and evaluate if barriers can serve their function, as well as it shall enable continuous improvement on barrier strategy and elements. In addition integrity management has to define performance requirement for operation so that it is in line with the barrier strategy.

N-005 defines managing integrity also as a systematic and cyclic change management process and defines the role of the Operator as being responsible for registering and assessing the consequence of any change that affect safety or performance. When safety assessment is made, the most important factors to be taken into account are human life and health; environment; and economic aspects as properties, operating interests. By using SIM, the Operator is able to document integrity, fitness-for-purpose and compliance with relevant national and international regulations of the structure throughout the asset's life. It provides a framework for implementing all integrity management activities, defining surveillance parameters, initiate response to surveillance findings and structural evaluations.

The SIM process has to ensure fitness-for-purpose even in situations when the source of change is not structural but it is a change in working personnel, corporate structure or the ownership of the assets. It is important that the knowledge gained through the integrity management can be transferred.

In the interpretation that NORSOK N-005 gives, integrity management systems:

- enable understanding the possible hazards and their nature to structures, as well as protection against hazards
- help establishing integrity strategy and performance criteria with respect to operation of the structures
- provide a basis for defining and executing surveillance tasks, monitor changes to structural condition, weights, variable loads, operating modes, regulations, etc.
- provide a basis for assessment and analyses in response to significant changes, may this be an emergency response, detailed assessment with structural analysis or a mitigation action in the form of structural repair
- sets requirements for necessary competence
- makes it possible to revise the integrity management system itself if changes necessitate it

The NORSOK N-005 sets focus on the continuous improvement of the As-is surveillance (the cycle with the thick dashed lines in Figure 2.7). This means that SIM as a management system needs evaluation and improvement.

2.3.4 Elements of integrity management in N-005

2.3.4.1 Data for integrity management

There are two dimensions of data that N-005 uses: data types and data sources. Surveillance covers all of these types regardless of their point of origin (source).

Type categories:

- Design regime (the technical control framework for the design, fabrication and installation which includes regulations, standards, specifications, procedures)
- Configuration (describes the geometry, properties, dimensions, condition, weights).
- Variable actions (properties of and imposed loads from the physical environment and the operating activity. Categories of this type can be operating, extreme and accidental)

Source categories:

- Project as-built data concerning new facilities, systems, components
- Project as-built data concerning modifications to existing facilities, systems, components
- Service life 'as-is' data concerning changes to as-built data

The N-005 recommends the use of data management systems where all the acquired information is to be stored for the entire lifetime of the structure.

The data and information above is stored in document archives and information databases. The latter ones are suitable for managing large quantities of data, and are able to produce reports; it is typically an electronic system. Document archives commonly used for reports. Information databases store and process information on surveillance programmes, surveillance results, as-is weight control, as-is change register and as-is analysis models.

2.3.4.2 Engineering evaluation

The process of engineering evaluation is that the engineer(s), who possesses the necessary knowledge and competence to carry out this task, decides if, based on the available data (previously gained or fresh),:

1) immediate or scheduled compensating measures are needed (e.g. production shutdown, evacuate personnel, temporary reinforcements)
2) assessments are needed to gain more information on the impact of detected changes
3) further inspections needed
4) the current inspection programmes are adequate and they are performed well
5) the current inspection programmes are not satisfactory or they are not executed properly; in this case action is to be taken.

If it is not option 4) that is relevant for the given situation, it is part of engineering evaluation to initiate action (from assessment to the completion of compensating measures).

The process of engineering evaluation is that data is processed through three “filters”, as shown in Figure 2.8. In this case the filter means that if the severity of one finding, which can emerge during surveillance or assessment, exceeds the threshold of the filter, is being processed further. Findings that exceed the predefined threshold are called anomalies.

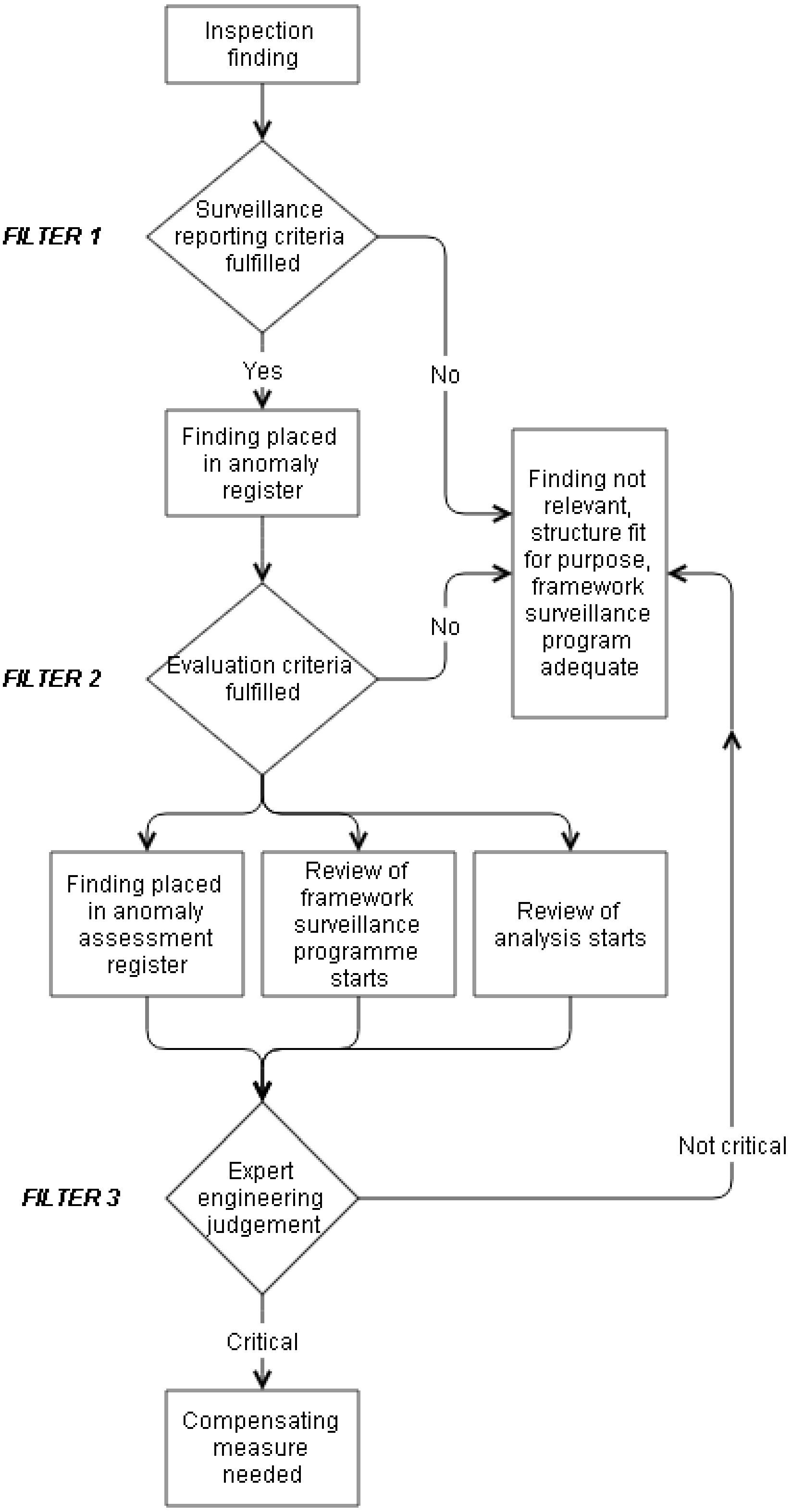


Figure 2.8: Engineering evaluation

The *first filter* is the predefined reporting criteria applied during the execution of inspection or surveillance. This is to ensure that relevant data is reported. Typical anomalies (topics that require reporting) include: corrosion, anodes, buckling, debris, damages (local or global), leakage, loosing, marine growth, weld defect, etc. Anomalies that pass this filter are in the anomaly register afterwards.

The *second filter* is the so called evaluation criteria which effectively covers the assessment triggers and KPIs that trigger the revision of surveillance programmes. With other words, the evaluation concludes that the "new information may significantly change the results of existing as-is assurance analyses or framework surveillance programmes" /3/.

The *third filter* is the expert engineering judgment. The anomalies in the anomaly assessment register are given to a specialist engineer who makes an assessment and if deemed necessary, performs structural analysis. Based on the results of the assessment, expert judgment is made on the necessity of compensating measures if the structure is not found fit-for-purpose.

For the structural integrity assessment, the N-005 defines the As-is analysis model portfolio. The portfolio identifies which analysis types are relevant for demonstrating integrity according to NORSOK N-001 or N-006 requirements. The analysis types are:

- Storm,
- Vessel impact,
- Earthquake,
- Redundancy,
- Fatigue,
- and Inspection planning.

The structural analysis model changes, that are necessary due to different anomalies, are stored in a model update log. It is possible that the updating process takes into account the different urgencies assigned to model types.

The way expert engineers make assessment covers the following steps:

1. Anomalies are received in the assessment register or communicated as an emergency request
2. The need for immediate compensating measure is evaluated or assessed
3. Decide which analysis needs to be updated with the anomaly
4. Anomalies are included in the model update logs with assigned urgency status
5. Run analyses if immediate assessment is needed (high urgency)
6. Evaluate results, and if needed take compensating measure

Assessment triggers are changes that are serious enough to question the validity of as-is assurance models. The NORSOK N-006 /4/ in section 4.2 lists the following conditions as structural assessment initiators: "

a) changes from the original design or previous assessment basis, including:
    1) modification to the facilities such that the magnitude or disposition of the permanent, variable or environmental actions on a structure are more onerous,
    2) more onerous environmental conditions and/or criteria,
    3) more onerous component or foundation resistance data and/or criteria,
    4) physical changes to the structure's design basis, e.g. excessive scour or subsidence, or relocation of mobile offshore units to a new location,
    5) inadequate deck height, such that waves associated with previous or new criteria will impact the deck, and provided such action was not previously considered.

b) damage or deterioration of a primary structural component or a mechanical component which contributes to maintain the assumed load conditions of the structure. Minor damage can be assessed by appropriate local analysis without performing a full assessment. However, cumulative effects of multiple damages shall be documented and included in a full assessment, where appropriate;

c) exceeding of design service life, if either
    1) the remaining fatigue life (including design fatigue factors) is less than the required extended service life,
    2) degradation of the structure beyond design allowances, or is likely to occur within the required extended service life.”

It is possible to define a set of key performance indicators (KPIs) to standardize, control and ease the decision on the number, severity and need for corrective actions. KPIs can be assigned to key elements of the surveillance and assessment processes. In the case of surveillance, these KPIs indicate:

- if adequate surveillance programmes to collect data exist
- what status the surveillance execution program has
- what status the evaluation of anomalies have

In the case of assessment, the KPIs indicate the need for numerical analysis update, hence the KPIs question:

- if analysis models covering all relevant action scenarios exist
- what status the anomalies in the assessment register have (assessed or not)
- what status the as-is assurance analyses have (with respect to model updates and analysis results)

2.3.4.3 Surveillance programmes

The basic surveillance unit in NORSOK N-005 is the surveillance task. Surveillance programmes are scheduled lists of surveillance tasks. The purpose of surveillance is detect any change that influences the as-is integrity assessments

The surveillance strategy forms the basis for Risk Based Inspection (RBI) assessments, which in turn results in the definition of the long-term framework surveillance.

The types of surveillance programmes that the N-005 lists are:

- Baseline: The purpose is to establish an as-is basis for change management later. It is performed shortly after commissioning. In case of life extensions, it is possible to make a baseline inspection at the start of the extended lifetime
- Framework: these are the inspections of the long-term integrity management surveillance strategy (in the “As-is surveillance” box in Figure 2.7)
- Special: special inspection programmes are carried out before the update of the long-term programmes. The incorporate inspections that will be part of the long-term program, but at the moment are not
- Unplanned: this is to investigate damages resulting from unexpected or exceptional events.

With respect to surveillance tasks, the N-005 defines three dimensions that are not independent of each other.

The *object* of inspection or surveillance: either documents onshore (as-built documentation, operational use and design regime limitations), or the physical asset offshore (structures or environment).

The *methods* of surveillance are dependent on the inspection object:

- in connection with documents, N-005 lists methods as document control or archiving, awareness of contents
- in case of inspecting the physical asset with respect to structures we can talk about visual and measurement type of inspections. Within *visual inspections* there is general visual inspection which is used to detect large anomalies and corrosion, and there is close visual inspection for small anomalies and cracks. Within *measurement* type of inspections one can find the different ultrasonic, electromagnetic, radioactive type of inspection methods
- if it is the physical environment that is subject to surveillance, the N-005 focuses on measurements in connection with fluid dynamics (waves, wind, current, tides, surge), temperature, ice, snow and soil sampling.

The third dimension is the *surveillance scheduling*, which is dependent on the risk that is to be mitigated and the used inspection method (probability of detection).

2.3.4.4 Surveillance execution

It is the surveillance campaigns that are the organizing structure for the surveillance tasks. They typically hold together tasks (or collection of tasks called work packages) that are scheduled somewhat close in time. For a given task, there can be some schedule changes, but if postponed by several years, than it is an execution anomaly and there has to be an engineering judgment on if this is possible, or can be justified.

Campaigns can organize tasks according to execution place and methods. E.g. onshore document surveillance and offshore physical surveillance.

There is a minimum of what defines the inspection task (surveillance task execution description):

- Campaign name and ID
- Work package name and ID
- Task ID
- Surveillance type (planned inspection type and deployment method)
- Location details
- Location drawings or plots
- Task description and special requirements

There are also defined data that a surveillance result has to contain:

- Inspection execution date
- Inspector name and company
- Inspection problems (yes/no)
- Description of any inspection problems
- Inspection type(s) and deployment method used
- Inspection findings (yes/no)
- Finding description and data
- Probable cause and possible consequence
- Corrective actions taken
- Recommended further action
- Reference to separate reports, images, videos.

2.4 DNV GL SIMS: Software tool developed by DNV GL to support the SIM process

2.4.1 Introduction

The SIMS (Structure Integrity Management System) program is developed by DNV GL Software in close cooperation with ConocoPhillips Norway. SIMS is a software implementation of the SIM process as defined in NORSOK N-005 /3/, integrating all elements of change control. The primary focus of the software is the Greater Ekofisk Area (GEA), but its versatile functionality enables it to be used for any platform area. It provides an easy to use graphical interface and advanced database techniques to support the following tasks in structural integrity management:

- Enables rapid data registration, collection and accessibility functions using a hierarchic data model that ranges from the individual structural member (e.g. a particular beam), through the organizing unit of a facility, up to the level of a field of platforms. The type of data can vary from structural element properties (e.g. geometry, flooding, inspection findings, etc.), to reports, documents or pictures.
- Has an “as-is” analysis model portfolio management including storing, archiving, status registration, model change management. The finite element models are linked to the change management.
- Helps quality assurance with the use of checklists.
- Supports surveying with the possibility of defining inspections and connected details in the program; organizing inspections in work packages and campaigns; printing hard copies of standardized inspection report templates; registering findings and forwarding them to evaluation.
- Facilitates eventual reporting obligation to the Petroleum Safety Authority (Codam), by automatic generation of required reports.
- Provides a traceable, hierarchic decision making processes by precisely defining roles and responsibilities of those involved in either analysis tasks or evaluation of survey findings.
- Includes an important management tool, the KPI aggregation. KPIs can be defined on all levels of data hierarchy for all stored data types. The low level KPIs can propagate to higher levels, enabling very high level overviews, using the traffic light analogy (green – OK, yellow – issues, red – not OK).
- Helps the user with 3D-viewer models that have information and status views on inspections, anomalies, repair history, geometry and dimensions. The 3D viewer models are in harmony with the analysis models.

- Enables to share information between stakeholders through a common and secure access to SIMS database in wide area network.
- Makes it possible and required that all data, reports, analyses are saved with a series of attributes (meta-data) which enable searching and indexing.
- It serves as a generic information tool which gives rapid access to key or often needed information.
- It also has various report generating functions, so that communication with those who do not have access to SIMS is eased.

The original concept that DNV GL's SIMS program is built upon takes its basis in the challenge that:

- Offshore structures usually operate for decades in extremely hostile environments
- There is significant cost and serious consequences connected to the operation, accidents and
- Many of the existing structures have reached of the original design life, but is intended to be operated in an extended time period (enhanced oil and gas recovery), DNV GL /8/, /9/
- Pressure on resources is relieved by the efficient data management system and control.

It is vital that structural integrity is efficiently managed to ensure continuous and safe operation. This inevitably invokes a need for an effective change management, since it is the responsibility of the operator to capture, evaluate and, if necessary, mitigate design premise changes which inevitably occur during the lifetime of a structure, which HSE and PSA are placing increased focus on. Examples of such changes are environmental effects (corrosion, fatigue, scour, marine growth, subsidence, wave statistics etc.) and operational effects (modifications, weight changes, risk classification, hazard scenarios etc.), but changes in regulations can also be expected. Emergency preparedness capabilities are dependent on long term data security, data storage and integrity management that is independent of personnel or organizational changes.

2.4.2 Definition of SIM in DNV GL's SIMS

As the SIMS brochure states: Structure Integrity Management (SIM) is the process of ensuring that the 'as-is' condition (corrosion, cracks, anodes, marine growth) and configuration (geometry, self weights, topside layout) of structures are known (surveyed) and correctly simulated, and that the results of hazard load analyses for foreseen design events (storm waves, earthquake, ship impact), satisfy company acceptance criteria and regulatory requirements. (9).

In Figure 2.9, which is a reproduction from /8/, the purpose of structural integrity management is shown as it is applied to DNV GL's SIMS program. It can be seen that the focus is on knowledge and change management. Reliability is defined as the mathematical combination of capacity and loading. From the introduction it is clear that the goal of DNV GL with the SIMS program is to focus on reliability and regulatory compliance over time. Hence diverging from installation as-is condition is seen the biggest threat. This includes on the capacity side deterioration effects, structural modifications, etc. On the loading side it can also be configurational changes or increased knowledge on hazard actions (e.g. ship impact curves).

It can be seen that configuration (structure and platform) appears on both sides (capacity and loading). The arrow on the capacity side points to the jacket, on the loading side to the topside. This implies that the tracking of topside loading changes has increased focus on the right side.

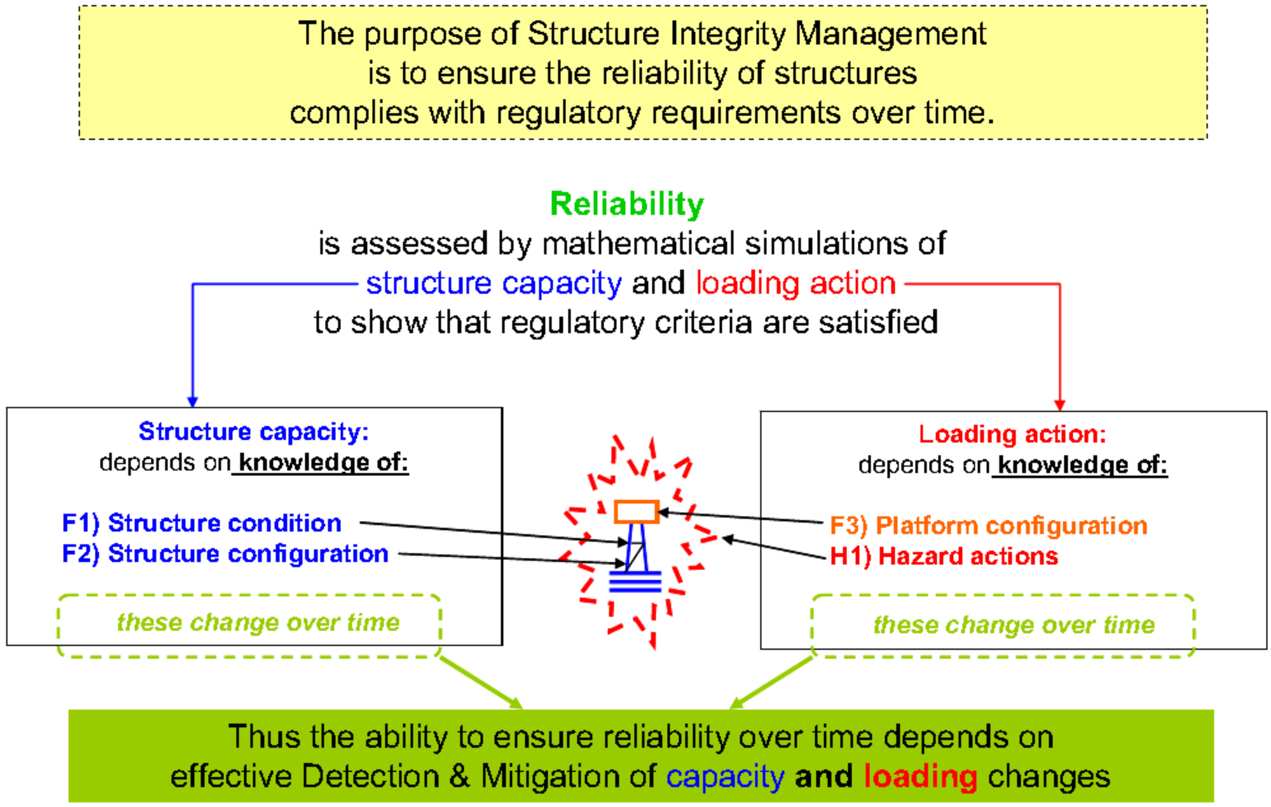


Figure 2.9: The purpose of Structure Integrity Management, source /8/

The objective with Figure 2.10, which is also a reproduction from /8/, is to show that 'Inspection' and 'Assessment' activities are integrated in the same environment (i.e. the SIMS system). It preserves parts from the original concept of API RP2SIM /1/, as Data – Evaluation – Strategy – Execution/Program, but extends it with practical requirements.

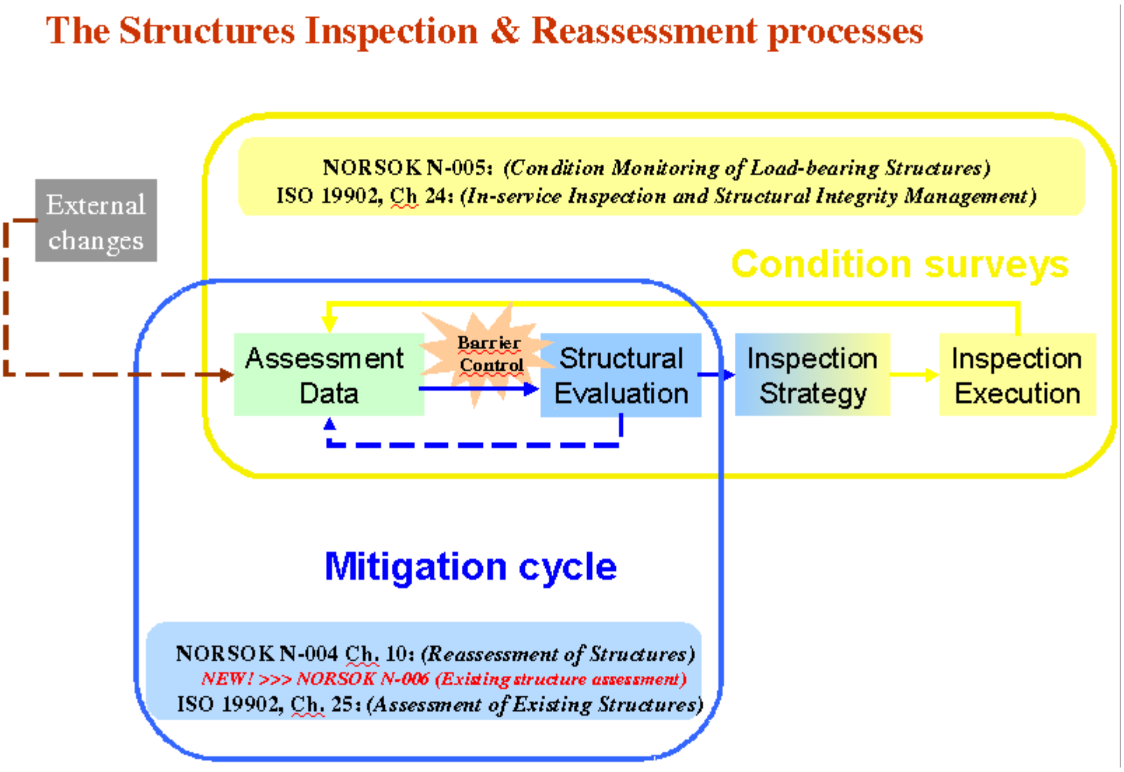


Figure 2.10: Definition of SIM process, source /8/

2.4.3 Analysis model portfolio

There is a certain tool in SIMS called the *As-is Assurance analysis portfolio and Status Overview matrix* which:

1. defines the required types of analyses for each Major Structure Area
2. gives an overview of the model portfolio compliance (AAm, AAc, etc.)

In Figure 2.11 which is a reproduction from /8/ an example is shown of the status overview matrix. It has to be emphasized that this is an example only and does not contain real information on the model/analysis/regulatory compliance status of the different platforms.

The major structures are in the rows of the matrix, and necessary analyses are in the columns. For each analysis there are two columns, one of this defining if the particular analysis is required for the platform (AAm), the second showing the status of the analysis.

The statuses are color-coded in the two columns with the following legend.

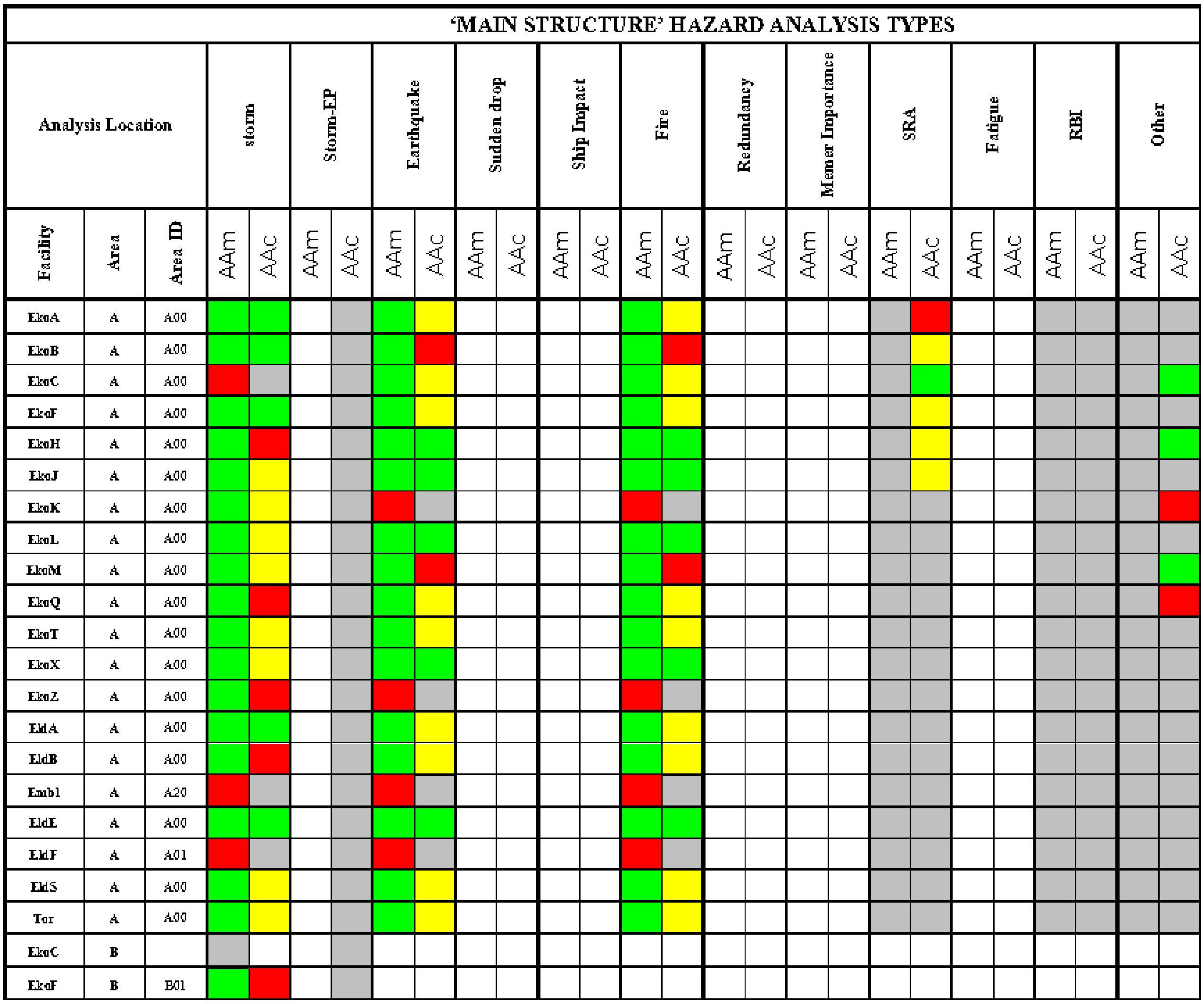
In the required (AAm) column:

- White – has not been defined if the model is required
- Red - model is required but has not been stored in SIMS
- Green - model is required and can be found in SIMS

- Grey - model is defined as not required

In the status column (AAc):

- Red - analysis in major non-compliance with design requirements
- Yellow - analysis in minor non-compliance with design requirements
- Green - analysis in compliance with design requirements
- Grey - no status exists or model does not exist



			'MAIN STRUCTURE' HAZARD ANALYSIS TYPES																							
Analysis Location			storm		Storm-EP		Earthquake		Sudden drop		Ship Impact		Fire		Redundancy		Memer Importance		SRA		Fatigue		RBI		Other	
Facility	Area	Area ID	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc	AAm	AAc
EkoA	A	A00	🟩	🟩		▨	🟩	🟨					🟩	🟨					▨	🟥			▨	▨	▨	▨
EkoB	A	A00	🟩	🟩		▨	🟩	🟥					🟩	🟥					▨	🟨			▨	▨	▨	▨
EkoC	A	A00	🟥	▨		▨	🟩	🟨					🟩	🟨					▨	🟩			▨	▨	▨	🟩
EkoF	A	A00	🟩	🟩		▨	🟩	🟨					🟩	🟨					▨	🟨			▨	▨	▨	▨
EkoH	A	A00	🟩	🟥		▨	🟩	🟩					🟩	🟩					▨	🟨			▨	▨	▨	🟩
EkoJ	A	A00	🟩	🟨		▨	🟩	🟩					🟩	🟩					▨	🟨			▨	▨	▨	▨
EkoK	A	A00	🟩	🟨		▨	🟥	▨					🟥	▨					▨	▨			▨	▨	▨	🟥
EkoL	A	A00	🟩	🟨		▨	🟩	🟩					🟩	🟩					▨	▨			▨	▨	▨	▨
EkoM	A	A00	🟩	🟨		▨	🟩	🟥					🟩	🟥					▨	▨			▨	▨	▨	🟩
EkoQ	A	A00	🟩	🟥		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	🟥
EkoT	A	A00	🟩	🟨		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	▨
EkoX	A	A00	🟩	🟨		▨	🟩	🟩					🟩	🟩					▨	▨			▨	▨	▨	▨
EkoZ	A	A00	🟩	🟥		▨	🟥	▨					🟥	▨					▨	▨			▨	▨	▨	▨
EldA	A	A00	🟩	🟩		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	▨
EldB	A	A00	🟩	🟥		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	▨
Embl	A	A20	🟥	▨		▨	🟥	▨					🟥	▨					▨	▨			▨	▨	▨	▨
EldE	A	A00	🟩	🟩		▨	🟩	🟩					🟩	🟩					▨	▨			▨	▨	▨	▨
EldF	A	A01	🟥	▨		▨	🟥	▨					🟥	▨					▨	▨			▨	▨	▨	▨
EldS	A	A00	🟩	🟨		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	▨
Tor	A	A00	🟩	🟨		▨	🟩	🟨					🟩	🟨					▨	▨			▨	▨	▨	▨
EkoC	B		▨			▨																				
EkoF	B	B01	🟩	🟥		▨																				

Figure 2.11: As-is assurance analysis portfolio and overview matrix, source /8/

NB! This figure does not contain real information on the status of the plaforms

In Figure 2.11 the first column is the facility code, the second is the area code within the facility. The following Major Structure Areas can be defined: A (Topside), B (Bridge), C (MSS – module support structure), F (Flare), G (GBS – gravity based structure), H (Helideck), J (Jacket Main), K (Crane Pedestal), T (Jacket Bridge), W (Seabed Template/Wells), M (Module), X (Foundation).

2.4.4 The structure of DNV GL's SIMS

SIMS has four portals: ***S**urvey, **A**nalysis, **F**ind* and ***E**nsure*, which are denoted with the first letter in lowercase (i.e. SIMS-s, SIMS-a, etc.) /8/.

***S**urvey* covers the functions of *Change detection*. This can be either on-site condition surveys, or weight- and configuration surveys (monitoring SAP as-built databases, offshore layout surveys, offshore level and distance surveys, offshore free-board surveys and GPS subsidence monitoring).

***A**nalysis* covers the assessment of anomalies. First all anomalies, that are evaluated if they trigger an assessment, are registered in the “Change register”. The changes are assessed and, if found to have a “High/Medium” impact, transferred to the analysis model “Change logs”, for later or immediate implementation in the As-is Assurance Analyses.

***F**ind* functionality is the Document archive and Key Information tools. Main purpose is to store Design and As-is Assurance documentation.

***E**nsure* is the functionality to make sure that the Survey and Analysis activities are consistently and correctly executed, (i.e. there is a follow-up of the findings of the surveys later in the analyses) and that any major hazards detected are mitigated in a timely manner (i.e. there is a response given to the detected changes to maintain regulatory compliance). This is achieved by the generation of KPI summaries and “Annual Structure Integrity Status” (ASIS) reports based on KPI data stored in the Survey and Analysis portals and in QC checklists (i.e. there are warnings given, by the use of aggregated KPIs, if follow-up or response measures are not taken).

2.4.4.1 SIMS Analysis Portal (SIMS-a)

The main purpose of the analysis portal is to provide an interface for storing, accessing and updating structural computer models. The actual analyses do not take place here (i.e. SIMS is not a FEA or CAE software, but more a library)

Models and statuses connected to models

The models are stored as 'As-is' Assurance models (AAm) in designated AA folders (one folder for each Major Structure Area of a facility). The AAm models contain everything that is needed to run an analysis, i.e. input files for geometry, permanent loads, variable loads as well as run-scripts that ensure that input files are read and executed in the intended order and with the intended interpreter settings. The AAm status represents the model's compliance with the real as-is situation may it contain a list of pending changes from previous anomaly assessment with respect to geometry, environmental condition or regulatory issues. The AAa status of the AA model represents the regulatory compliance of the model in connection with the analysis results. The AAa status is manually set by the analysis responsible. The AAQC status of the model is also a manually set value which is the quality check status of the model (also set by the analysis responsible). The AASAS (Structure Analysis Summary) status of the model, on the other hand, is a generated status from the data in the AASAS checklists.

The highest level status connected to an AA model is the AAc status, which aggregates all the mentioned statuses above.

The 3D viewer models have to represent the as-is condition of the facility with respect to member geometry, as well as they have to match the analysis models when it comes to member and node numbering.

Change management

SIMS is designed to both register and follow-up the mitigation of changes. Change can be physical (e.g. damaged member) or environmental or a regulatory change compared to the design conditions.

When a change event (i.e. anomaly) is created the following data are registered:

- the details of the change (large amount of data including where the change has taken place, who registered and approved it, and the description of the change)
- the source of the change (survey, analysis, operation, regulations, other)
- the type of change (e.g. anomaly, criteria / methodology, environment, model improvement, modification, operation, weight & configuration)
- the category of change (i.e. the criticality: low – medium – high)
- the schedule of the change (already implemented / tentative)
- the supporting documentation of the change can be saved
- reference can be made to affected AA models, which triggers the recalculation of the analysis portfolio and overview matrix.

The registered changes have to be implemented one-by-one for the linked AA models.

2.4.4.2 SIMS Survey Portal (SIMS-s)

The function of the Survey portal is to organize and register inspections and findings. There are a number of inspections that the analyses prescribe for a given structure. In SIMS, the individual inspections are organized into campaigns which can typically involve more than one facility. It is common to put all inspections for a given year in one campaign. Within the campaigns, there are the work packages that typically cover one area or zone of one structure.

The typical inspection work process is shown in Figure 2.12.

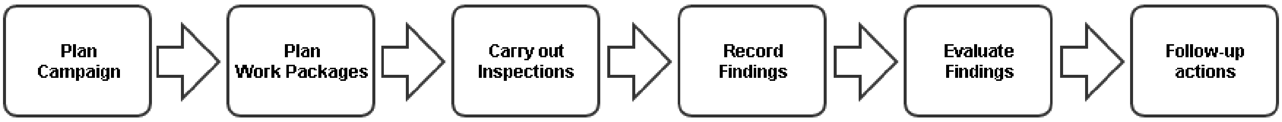


Figure 2.12: Work process of inspections in SIMS, based on /9/

SIMS enables Ad-hoc findings also, i.e. findings that do not come from an organized campaign.

After the findings from the inspections are registered, there is an evaluation phase where personnel use (structural) engineering judgment to decide on the further proceedings in connection with the finding, i.e. if further assessment is required. If it is deemed critical enough it is put into the change-assessment register for expert assessment the same way as a change event.

2.4.4.3 SIMS Find Portal (SIMS-f)

The function of the Find portal in SIMS is to provide access to facility related documents, even if the document has been attached to a sub-level of the facility. This way it provides a searchable overview of all connected documents. Each document is to be “tagged” with a defined set of categorized meta-data. The linked document does not have to be a physical file stored in SIMS. It can also be just a reference to a document.

In connection with meta-data, it has to be noted that not only documents, but also facilities, areas, campaigns, inspections have a good number of meta-data fields.

In addition the structure can be viewed with the 3D viewer and it can be seen what areas belong to the facility (the possible choices were mentioned in connection with Figure 2.11).

The Find portal is the highest level managerial summary platform in SIMS to get an overview of the statuses of the facilities including analyses and inspections.

2.4.4.4 SIMS Ensure Portal (SIMS-e)

The Ensure portal contains the CODAM tool, DB reports, KPI summaries, the various reports and the Activity plan tool.

The CODAM tool is used if standardized reports have to be issued to the Petroleum Safety Authority Norway (PSA).

The DB reports tool is suited for making customer specific reports from the data stored in SIMS.

The KPI summaries tool is a very high level overview tool that sums the statuses within the facility. In addition to summing it also has trending functions, i.e. it is possible to see if the sums got better or worse in the course of the years.

The ASIS report “enable users to create As-is Structure Integrity Summary (ASIS) reports. These are typically generated at the end of each year and provide integrity performance overviews at aggregated and detailed levels.” /9/.

The other report types that are available in SIMS-e are: ACT – Analysis Change Task Summary, SCA – Structure Condition Anomaly Summary, DFIO – Design, Fabrication, Installation, Operation Resumé, SAS – Structure Analysis Summary.

The Activity plan tool is a project management tool tailored for the needs of the SIMS software.

2.4.5 Conclusion on DNV GL SIMS as a tool supporting the SIM process

The SIMS tool developed by DNV GL fully supports the SIM process in harmony with the requirements given in NORSOK N-005, API RP2SIM and ISO 19902. SIMS is a solution that integrates the inspection (surveillance) and assessment activities in the same environment, and provides software functionalities for all the main building blocks of SIM.

SIMS puts change management in focus and incorporates solutions to register, evaluate and mitigate risk with the following SIM processes: Manage survey changes, Manage analysis changes, Find information, Ensure integrity.

2.5 Conclusion on the interpretation of structural integrity management in API RP2SIM, ISO19902 and NORSOK N-005

From the three standards that were subject to study in the previous sections API RP2SIM and ISO19902 are very similar in the definitions they use for Structural Integrity Management, while N-005 has somewhat different formulations. On the other hand in essence and with respect to basic processes of SIM they are quite alike.

All three standards are very general in their definitions, and the described principles could be used anywhere for any structure, but the details of certain processes limit the actual usage to a specific geographic area /1, section 1/.

The three standards are very similar in what they see as the fundamental building blocks of SIM.

There are differences between the API/ISO and NORSOK standards. One, that is very obvious, is that the API/ISO uses the word *inspection*, while NORSOK is using *surveillance*. In the API/ISO's inspection only the physical inspection of assets is included and eventual regulatory changes or other sources that require document inspection come into the process via other channels. In the NORSOK standard the term surveillance deliberately incorporates activities where inspection is targeted at documentation or the physical surrounding of the asset. The NORSOK standard intends to emphasize with this that the Data block contains information not only from structural inspection.

Difference can also be found how the four basic blocks of SIM are named in the standards. API/ISO is using *data – (engineering) evaluation – strategy – program* while NORSOK is using *data – engineering evaluation – surveillance programmes – surveillance execution*.

If we look at the contents of strategy or surveillance programmes in connection with the inspection of the physical asset, very similar inspection programmes can be found (baseline, framework/routine and special). However it is clear that in the API/ISO standards the qualitative risk is more focused, and the strategy block includes measures that modify the platform connected risk and consequence in qualitative terms. The NORSOK standard is more based on quantitative assessment for developing an inspection program.

It can be noticed that the NORSOK N-005 /3/ often contains or prescribes details of the scope of data from the different sources. One has a feeling that the author(s) of NORSOK N-005 had a practical implementation in mind while writing the standard, and they felt that it was important to give guidance on that as well.

It can also be noted about the new N-005, that it is visible from Figure 2.1 and Figure 2.7, that N-005 has a more complex picture of Structural Integrity Management and puts emphasis on, as well as tries to regulate the processes outside the four main blocks of SIM. This is a rather important difference, because it sets focus on evaluating and improving the process of SIM also. This is an additional loop that can only be found in N-005. The intention with this is to outfit the core processes with a barrier context based on PSA recommendations /11/.

3 Barrier control

3.1 Introduction

Accidents can be very diverse. There can be a plethora of hazards and a series of accident scenarios. “The event sequences that lead to unintentional harm appears to be very different, the consequences range from trivial to catastrophic, and accidents occur in very different social and technological setting”, SINTEF /12/. Barriers and its theoretical predecessors are used in the risk analysis and risk management regimes of socio-technical systems in order to help tackling the problems and diversities connected to accidents in a systematic way.

Barriers are intentionally planned functions to prevent, control or mitigate the propagation of a hazardous event from making harm or reach its full consequences. It is common to have a series of barriers, each implementing a particular function, the serial sum of which is intended to cover all the foreseeable failure scenarios connected to the hazard.

The API RP2SIM /1/ and ISO19902 /2/ standards have almost no references to barriers. In the proposed version of the new NORSOK N-005 /3/ there is a parallel drawn between the Structural Integrity Management and “rational method of managing safety-critical systems, activities and elements (barriers)” /3, section 1/. The ISO 17776:2000 /13/, ISO 31000:2009 /14/ and the Principles of barrier management in the offshore industry from PSA /11/ are named as sources.

The purpose of Structural Integrity Management is to ensure a fit-for-purpose condition. Barriers are included in this thesis, because SIM has to ensure that all measures are taken to maintain structural safety at an acceptable level. “This may imply that also preventive mitigations to reduce or control actions and hazards, limit the structures sensitivity to actions and hazards, and robustness to tolerate damage shall be managed. In this context, this standard (NORSOK N-005) is based on barrier management of safety critical technical systems and components, organizations and operations (…). This includes the principles and strategies for establishing and maintaining barriers so that their function is safeguarded throughout the life of a facility.” /3, section 4.4/

3.2 Development of the barrier concept

Using the expression barrier in its current meaning in connection with risk and safety originates partly form Gibson's energy model /15/ which aimed at classifying sources of accidents and injury based on the forms of the physical energy involved. The goal of the energy model was to systematically list causes of accidents /12/. The origins of the barrier concept are also partly based on Haddon's /16/ “barrier perspective and its implications for accident prevention. The basic idea is that accidents occur when objects are effected by harmful energy in the absence of effective barriers between energy source and the object” /12/. In Figure 3.1 the barrier concept is shown.

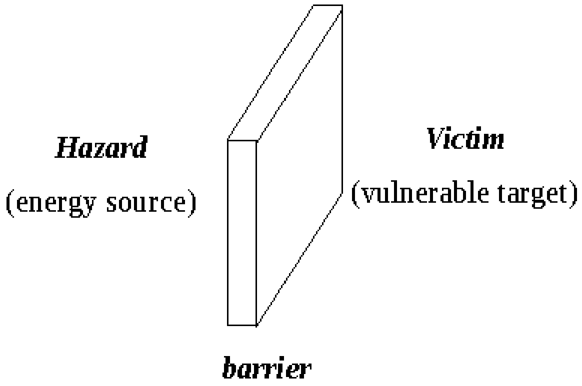


Figure 3.1: Barrier applied in the energy model, based on /12/

The hazard (potential source of harm) itself is the energy exchange, i.e. the energy has a quality and quantity that is harmful for the target or victim (e.g. humans, environment or assets can be damaged). DNV GL in its report to the Norwegian Shipowner Association /17/ names eight basic forms of energy that can be sources of harm or hazards, if control is lost over these. The eight forms of energy (Movement, Chemical, Radiation, Electricity, Gravity, Temperature, Biological and Pressure) are shown in Figure 3.2. The barrier stands between the hazard source and the victim.

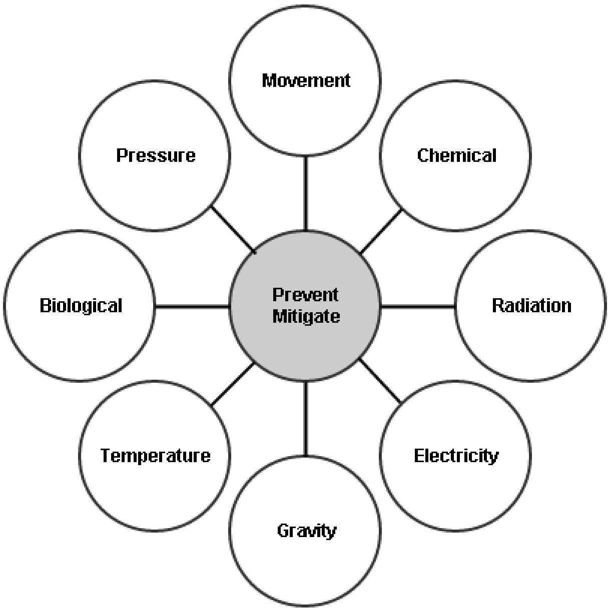


Figure 3.2: Eight basic forms of energy, based on /17/

Haddon's ten strategies are listed below, from /16/ which is the original article. The strategies are also listed from Lundteigen's presentation /18/ which is a more modern formulation and highlights the 3 classes of measures in the strategies. The term barrier itself has a rather physical meaning in Haddon's list, but this meaning can be extended with a more abstract interpretation. The term barrier can include a more functional view /12/ where the goal, task and function is the barrier. From this point of view all the 10 strategies can be looked upon as barriers.

Haddon's 10 strategies (original) /16/:

1. The first strategy is to prevent the marshalling of the form of energy in the first place
2. The second strategy is to reduce the amount of energy marshalled
3. The third strategy is to prevent the release of the energy
4. The fourth strategy is to modify the rate of spatial distribution of release of the energy from its source
5. The fifth strategy is to separate, in space or time, the energy being released from the susceptible structure, whether living or inanimate
6. The very important sixth strategy uses not separation in time and space but separation by interposition of a material 'barrier'
7. The seventh strategy, into which the sixth blends, is also very important - to modify appropriately the contact surface, subsurface, or basic structure, as in eliminating, rounding, and softening corners, edges, and points with which people can, and therefore sooner or later do, come in contact.
8. The eighth strategy in reducing losses in people and property is to strengthen the structure, living or nonliving, that might otherwise be damaged by the entry transfer.
9. The ninth strategy in loss reduction applies to the damage not prevented by measures under the eight preceding - to move rapidly in detection and evaluation of damage that has occurred or is occurring, and to counter its continuation and extension.
10. The tenth strategy encompasses all the measures between the emergency period following the damaging energy exchange and the final stabilization of the process after appropriate intermediate and long-term reparative and rehabilitative measures.

Haddon's 10 strategies (reformulated) /18/:

Reducing the hazard:

1. Prevent the (creation of) hazard or threat
2. Reduce the amount of hazard or threat
3. Prevent the release of hazard or threat
4. Modify the rate of release from its source
7. Modify the relevant properties of the hazard or threat

Build physical barriers:

5. Separate in time or space the released hazard or threat
6. Separate with physical means of physical protection

Protect and rehabilitate victims:

8. Make the victim more resistant to the damage
9. Reduce the further development of damage (in time and amount)
10. Stabilize, repair, and rehabilitate from damage

Barriers are also the part of the “Swiss Cheese Model” of accident causation from Reason /19/. The barrier model from Haddon can be used for smaller and larger systems as well, but for larger systems a layered defense mechanism (“defenses in depth”) is better. This concept is shown in Figure 3.3 which is based on /20/. It is typical for these systems that accidents do not develop from single, isolated failures. The successive protective layers are represented with slices of cheese, with each layer having its weaknesses (holes). The development of a hazard is stopped if one layer fails but the successive layer stops the propagation. On the other hand the hazard can develop into losses if in one particular hazard scenario the weaknesses “align” and a hazard can be realized, the hazard can propagate through the barriers. In the Swiss cheese model barriers can be physical, organizational, technical and human also.

The weaknesses in each layer can be due to *active* or *latent* failures. *Active* failures have a direct influence on the accident and originate from the errors of humans, their unsafe actions or the errors of technology. *Latent* failures, on the other hand, do not have direct influences or consequences for the accident causation, but still they let accident scenarios to develop. These are unrevealed defects or flaws in the system. It has to be noted in connection with Figure 3.3 that the layers of defenses seem independent, but they are not. The connectedness and interdependency of layers (e.g. energy supply) must be subject to analysis.

The weaknesses or “holes” are not necessarily constant but indeed can change with environment factors, time/aging, and are dependent on influencing factors.

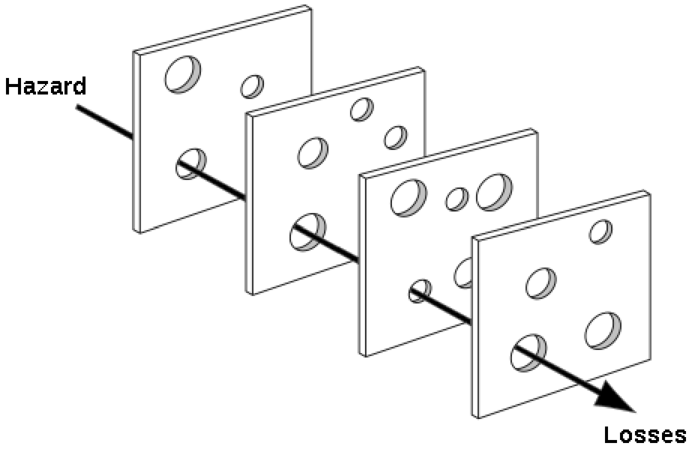


Figure 3.3: Swiss cheese model, based on /20/

In summary it can be said about the development of the barrier concept that:

- in its early forms the term barrier is a concrete, physical structure or a physical countermeasure, but later on, applying a more functional perspective, barrier becomes the “tasks that are necessary to adequately control a specific hazard” /12/
- a development in the terms of consequences can be noticed also. While the focus is on the harm of the individual in the beginning, it shifts to the loss of control in large and complex systems later on.

3.3 Terms in connection with barriers

3.3.1 Definitions used by the Petroleum Safety Authority

This chapter presents the terminology used by the Petroleum Safety Authority (PSA) /11/ and Sklet /21/, /22/ in connection with barriers and barrier management.

As the Petroleum Safety Authority (PSA) defines in the Summary section of Principles for barrier management in the petroleum industry /11/ that barriers and barrier management serve the purpose of reducing and managing risk so that:

- any undesirable event is prevented from happening, or
- the consequences of such an event are reduced or eliminated.

PSA defines *barriers* as a very general term, as concepts. Barriers are “technical, operational and organizational elements which are intended individually or collectively

- to reduce possibility/ for a specific error, hazard or accident to occur,
- or which limit its harm/disadvantages.” /11/.

Barrier is the word to refer to the barrier function and barrier element with a one word term.

A *barrier function* is the role or the purpose that the barrier implements. This function can be “preventing leaks or ignition, reducing fire loads, ensuring acceptable evacuation and preventing hearing damage.” /11/.

It is the *barrier elements* that can have a physical meaning, it is the way or means of implementing the barrier function. A barrier element can be any “technical, operational or organizational measures or solutions which play a part in realizing a barrier function.” /11/.

The term *performance requirement* or *performance standard* is in very close connection to the barrier element, since these define the verifiable qualities that the barrier elements must possess to ensure that the barrier function is active and that barriers are effective. The qualities that performance standards define are “capacity, functionality, effectiveness, integrity, reliability, availability, ability to withstand loads, robustness, expertise and mobilization time.“ /11/.

The *performance influencing factors* are the conditions which can have an effect on the character of the defined qualities from the performance requirements. These are factors that strengthen or weaken the ability of barrier functions and elements to perform as intended.

The term *barrier strategy* is the answer to the risk picture. It describes and clarifies the barrier functions and elements to be implemented in order to reduce risk.

Figure 3.4, shows the structure and hierarchy of the terms above, used by PSA.

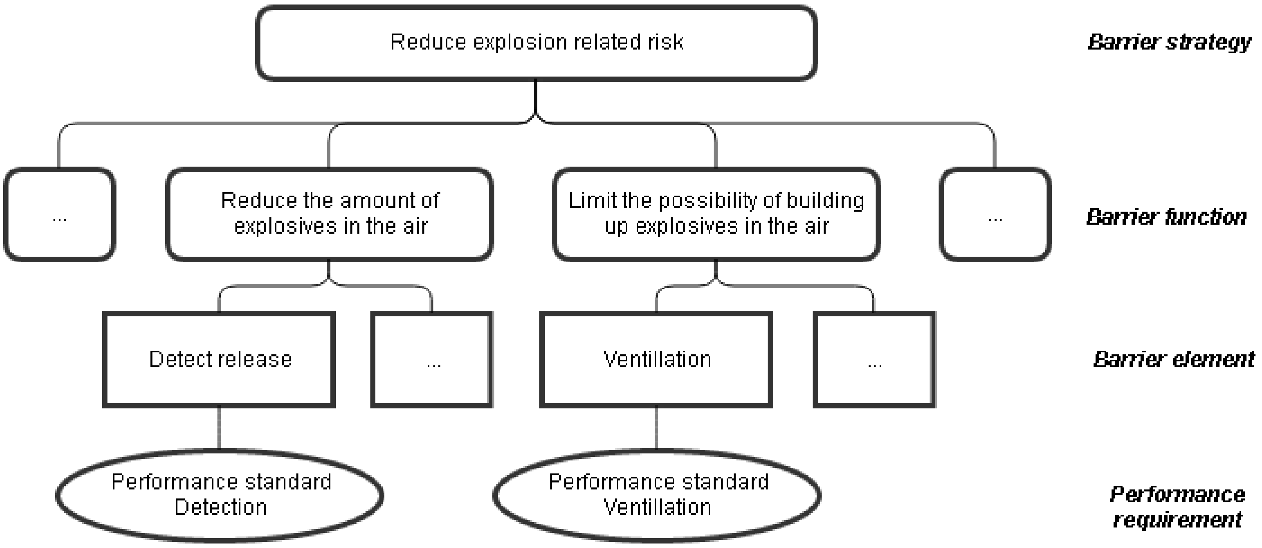


Figure 3.4: Structure of terms related to barriers, based on /11/

In Figure 3.5 the process of barrier establishment is shown. Developing barriers (strategy, planned elements and their influencing factors) is a risk treatment.

The process starts with establishing the context of the risk analysis. The context includes all the conditions that must be taken into account, and which form the boundary conditions of the analysis and operation later on. Regulatory prescriptions, company strategies for the context. Also the design of the facility the barriers are formed for have to be taken into account.

The role of the subsequent risk assessment is to establish a risk picture. This includes that all hazards and their possible consequences have to be revealed. As an answer to the hazards, barrier functions and barrier elements are defined. Afterwards the effectiveness of barriers can be estimated with risk and safety analyses. The results have to be evaluated in a way, that besides the (numerical) results of assessments, regulatory provisions or company rules are also taken into account. The latter may override the results of an analysis.

In the risk treatment step it is reviewed if additional measures, beyond those indicated by the quantitative analyses, are needed. The findings of the previous steps are detailed in the barrier strategy and specific performance criteria are formulated.

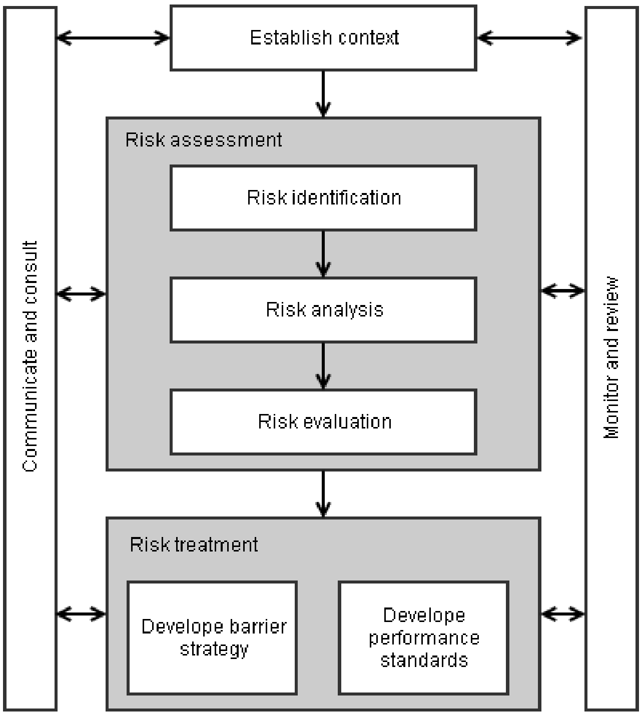


Figure 3.5: Establishing barriers in the design phase, based on /11/

The PSA also defines *barrier management* in /11/ as process of activities with the intention to establish and maintain barriers. The goal of barrier management is to maintain the barrier functions.

In Figure 3.6 the process of barrier management is shown.

Barrier management takes its starting point in the initial establishment of barrier strategy and performance standards (Figure 3.5) based on the risk picture. This basis must be monitored, reviewed and possibly updated during the execution or operational phase. Measurement and verification has to be carried out in order to be able to secure continuous improvement and to achieve robust barriers throughout the whole life cycle.

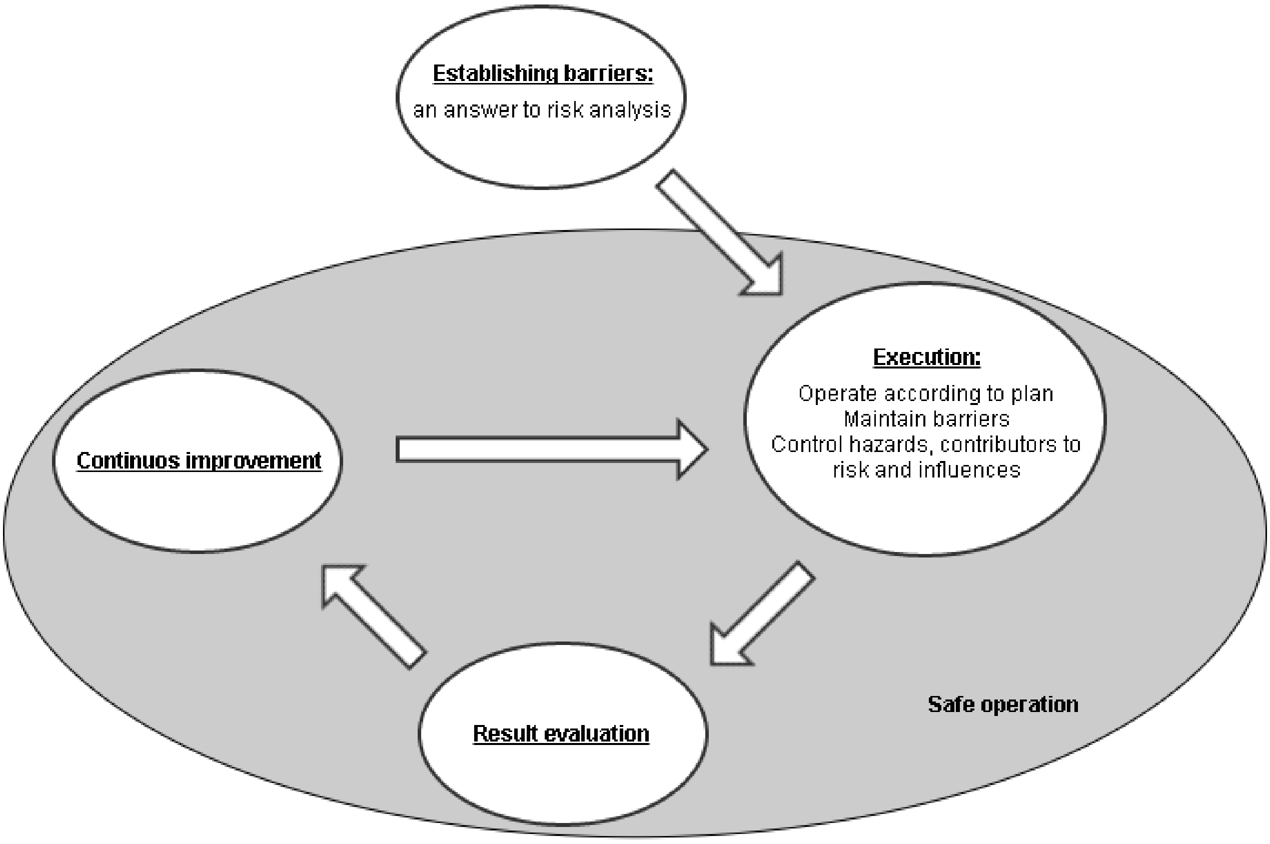


Figure 3.6: Barrier management, partly based on /11/

The proposed new version of NORSOK N-005 /3/ gives a good summary about what shall be included in a barrier management system: "Barrier management includes having strategies for protecting a facility against hazards. The means of protection in this context is by barriers with a specific function (role and purpose) to hinder the realization of the hazard or significantly reduce the consequence of this hazard. Further, the strategies shall include means of how to manage the use of the barrier and how to maintain the barriers, so that the barriers' function is safeguarded and meet the prescribed performance criteria throughout the life of a facility. The barrier management shall consist of:

- A barrier strategy and performance requirements to these barriers.
- Operation of the facility in accordance with the barrier strategy, performance requirements and any operational limitations indicated in in the barrier strategy, or that the barrier strategy is based on.
- Maintenance of the barrier elements so that they are able to meet the performance requirements and fulfil the role of the barrier function.
- Monitor barrier performance and evaluate the barriers.
- Continuous improvement."

3.3.2 Definitions used by Sklet

Sklet defines barriers in his PhD Thesis /21/ in a rather similar way to PSA's definition, as “Safety barriers are defined as physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents. The means may range from a single technical unit or human actions, to a complex socio-technical system” /21/. He also uses the definition that barriers are technical, human, operational, or organizational factors that influence the accident sequences.

The PSA defined the main components of the barriers as barrier functions and barrier elements. In contrast with this to a certain extent Sklet defines the barrier function and the barrier system with the following meaning: “It is useful to distinguish between barrier functions and barrier systems. Barrier functions describe the purpose of safety barriers or what the safety barriers shall do in order to prevent, control, or mitigate undesired events or accidents. Barrier systems describe how a barrier function is realized or executed. If the barrier system is functioning, the barrier function is performed. If a barrier function is performed successfully, it should have a direct and significant effect on the occurrence and/or consequences of an undesired event or accident” /21/. It can be seen that the meaning of barrier function is entirely similar to PSA's definition. On the other hand, barrier system appears to be similar to barrier element. In this thesis the use of barrier element is preferred.

Sklet defines performance indicators for barriers as attributes to describe the performance of the safety barriers. These attributes are functionality/effectiveness; reliability/availability; response time; robustness; triggering event or condition; and the resources needed to implement and maintain the barrier function.

The functionality stands for how much the barrier can perform its functions in the conditions and environment it is situated in. The reliability is the capability to perform when needed. The response time is the time between occurrence of deviation and fully implementing the barrier functions. The triggering event is what activates the barrier functions. The robustness is the resilience of the barrier against loads.

These attributes cannot be applied to all kinds of barriers, and usually not all the attributes can be applied at the same time.

3.3.2.1 Categories of barriers

The term barrier is rather broad. It incorporates physical and non-physical elements. This results in that they can be categorized from various aspects.

Among the function of barriers it is possible to distinguish between preventive, controlling or mitigating. This depends on where the barrier is placed within the accident sequence.

The barrier elements (the implementation of the barrier) can be:

- *active* or *passive*: passive barrier can be e.g. a dam, active an ventilator that prevents the build-up of explosives in a confined area

- *physical/technical* or *human/operational*: physical barrier elements are all that can be touched, while operational barriers are “human actions or responses that results in the activation of a physical barrier, thereby enhancing the total system reliability”, IADC: Drilling lexicon /23/
- *permanent* or *temporary*: permanent barriers can typically be built physical barriers, while temporary ones can be removed, hence cease the barrier function
- *continuously functioning/on-line* or *activated/off-line*: these categories are mostly within the aforementioned temporary barrier category. Continuously functioning barriers can be sensors that send data on a permanent basis, while activated barriers can be emergency equipment.

4 Robustness

4.1 Introduction

Robustness is desirable property in structures and systems. Even without a proper definition, the term robustness implies an association with strength, endurance, invulnerability, durability and hard-weariness. Robustness is the quality that defines how structures behave outside their operational envelope and it defines their potential to survive accidents.

In the following sections there will be examples on how robustness is defined in connection with structures and how it is defined in other disciplines. It will be shown what methodologies or approaches exist to ensure robustness in quantitative and qualitative ways.

4.2 Definitions of robustness

In this thesis, the main focus is on how robustness is defined from a structural point of view. However it is useful to look at how other disciplines define this term, since all the definitions reflect an aspect of robustness. This is essential for the given discipline, but may be important from a structural point of view also. The following sentences are cited from Baker /24/.

In software engineering:

> The ability to react appropriately to abnormal circumstances (i.e. circumstances “outside of specifications”). A system may be correct without being robust.(cited in /24/ from Meyer /25/).

Product Development and QC:

> The measure of the capacity of a production process to remain unaffected by small but deliberate variations of internal parameters, so as to provide an indication of the reliability during normal use.

In connection with ecosystems:

> The ability of a system to maintain function even with changes in internal structure or external environment. (cited in /24/ from Callaway et al. /26/).

Control theory:

> The degree to which a system is insensitive to effects that are not considered in the design. (cited in /24/ from Slotine and Li /27/).

In statistics:

> A robust statistical technique is insensitive against small deviations in the assumptions.

Design optimization:

> A robust solution in an optimization problem is one that has the best performance under its worst case (max-min rule). (cited in /24/ from Kouvelis and Yu /28/).

It is common in the definitions above that they define robustness as a property that helps reducing the consequences of changes or deviations from ideal conditions; as well as that it hinders the propagation of changes and deviations, so that they remain localized and leave the system unaffected to the greatest possible extent.

4.2.1 Structural definition of robustness

The definition of robustness is formulated somewhat differently in the various design codes. This section gives an overview and comments on the definitions.

ISO19902 /2/

> In section 3.46: "*robustness: ability of a structure to withstand events with a reasonable likelihood of occurring without being damaged to an extent disproportionate to the cause"*
>
> In section 7.9: "*A structure shall incorporate robustness through consideration of the effects of all hazards and their probabilities of occurrence, to ensure that consequent damage is not disproportionate to the cause. Damage from an event with a reasonable likelihood of occurrence shall not lead to complete loss of integrity of the structure. In such cases, the structural integrity in the damaged state shall be sufficient to allow a process system close down and a safe evacuation, see Clause 10.*
>
> *Robustness is achieved by either*
>
> *a) designing the structure in such a way that any single load bearing component exposed to hazard can become incapable of carrying its normal design actions without causing collapse of the structure or any significant part of it, or*
>
> *b) ensuring (by design or by protective measures) that no critical component exposed to hazard can be made ineffective, or*
>
> *c) a combination of a) and b), above."*

EN 1991-1-7:2006 /29/

> In section 1.5.14: "*robustness: the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause."*
>
> In section 3.2: *ensuring that the structure has sufficient robustness by adopting one or more of the following approaches:*

> *1) by designing certain components of the structure upon which stability depends as key elements (...) to increase the likelihood of the structure's survival following an accidental event.*
>
> *2) designing structural members, and selecting materials, to have sufficient ductility capable of absorbing significant strain energy without rupture.*
>
> *3) incorporating sufficient redundancy in the structure to facilitate the transfer of actions to alternative load paths following an accidental event."*

4.2.2 Conclusion on the definition of robustness from a structural point of view

In summary, it is possible to conclude that:

- robustness is a derived property of the structure that comes from the aggregated properties of several structural members (in contrast with initial properties like yield strength), and it incorporates the direct and indirect effects of several initial properties
- robustness is in connection with circumstances that were unaccounted for or is in connection with know circumstances that were assumed to have very low probability
- the definition of robustness contains a meaning that structures shall withstand extreme events, and
- the definition of robustness has a meaning, that it is a property of the structure, that given an initial damage, it prevents consequences from being unacceptable relative to the initiating damage, and ensures that structures do not suffer a disproportionate collapse (e.g. progressive collapse)

4.2.3 Robustness expressed with the likelihood of failure

In connection with the definition of robustness, it is worth looking at how robustness can be expressed with the means of probability calculations.

The robustness definition is very well represented in the probability of disproportionate or progressive collapse in Ellingwood and Dusenberry /30/ referenced in Starossek and Haberland /31/

$$P(F)=P(F|DH)*P(D|H)*P(H) \qquad \text{Formula 4.1}$$

Where, P(H) is the probability of an abnormal event (hazard) that threatens the structure; P(D|H) is the probability of local damage D given the event H; and P(F|DH) denotes the probability of the failure F of the structure given there is a local damage D, given there is a hazard H.

It has to be noted that Formula 4.1 refers to one specific hazard, and one specific initial damage. This is accounted for in Formula 4.2, which is the modified form of Formula 4.1 taking the probability of failure from all hazards, all initial damages and all ways of progressive collapse.

$$P(F)=\sum_i \sum_j \sum_k P(F_k|D_j H_i) * P(D_j|H_i) * P(H_i)$$ Formula 4.2

There exist many different or overlapping definitions for robustness. Using Formula 4.1 it is possible to give expressive examples on the differences.

Aven /32/ defines vulnerability as the antonym of robustness: “Vulnerability: combination of the consequences and associated uncertainties given an initiating event”. Hence the definition of vulnerability covers the following elements: (C, C* , U, P , K|A). In Aven's definition the meaning of symbols is the following:

C	consequences
C*	prediction of C
U	uncertainty
P	probability
K	the background knowledge K

given that the initiating event A takes place.

This is in harmony with how Starossek and Haberland /31/ define vulnerability, see Figure 4.1, but is in contrast with their definition of robustness (not antonym). I.e. robustness in Figure 4.1 is only the last part of the combined probability, the chance of collapse, given the hazard and initial damage.

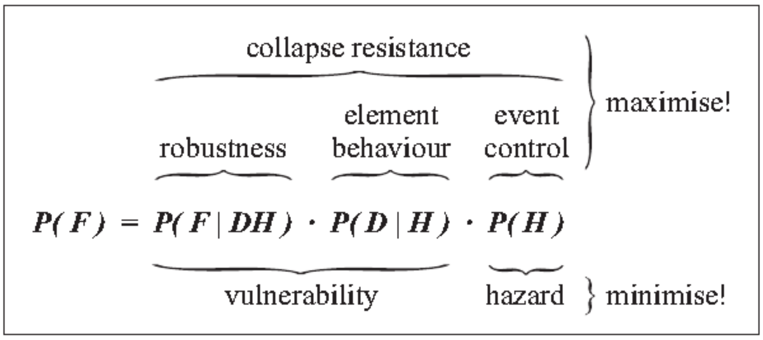


Figure 4.1: Probability of disproportionate collapse, source /31/

4.2.4 Robustness expressed as a calculated property

Faber et al. /33/ define the risk in connection with disproportionate collapse. They use a stepwise methodology with the below stages to analyze consequences:

1. there is an exposure to a hazard of any kind (not necessarily explosion)
2. a local damage results from the hazard in step 1
3. the structure may or may not survive (be disproportionately damaged) resulting from the initial damage.

This process is represented in Figure 4.2, which is reproduced from /33/.

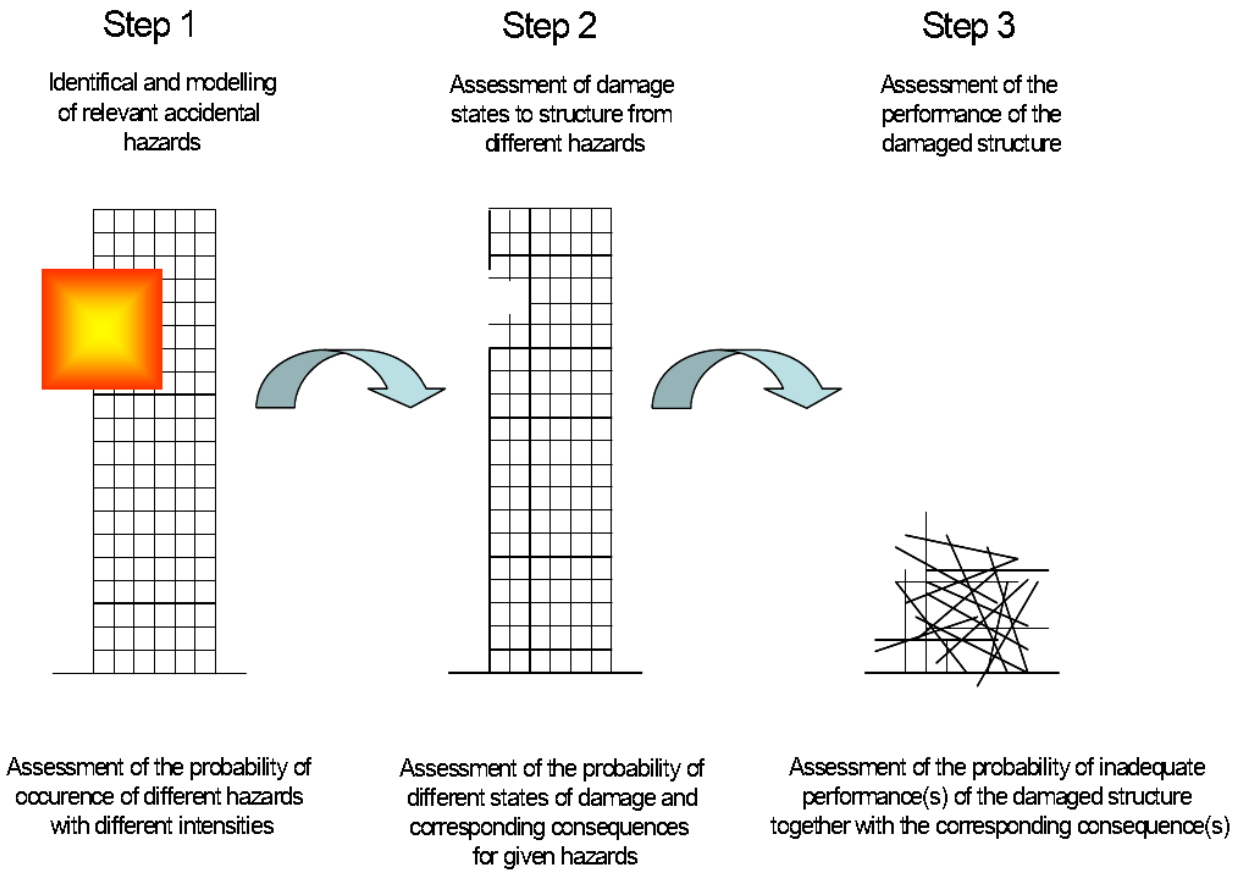


Figure 4.2: Steps of consequence analysis, source /33/

Faber et al. in /33/ states that robustness requirements are especially connected to step 2 and 3, namely hazard control is less the part of robustness, but preventing initial damage and preventing the propagation of initial damage is an essential part.

There are several approaches to quantify robustness, which can be classified in 3 categories:

- risk-based robustness index: the consequences are divided into direct and indirect consequences (i.e. initial damage and damage from the propagation)
- probabilistic robustness index
- deterministic robustness indexes (based on structural properties, pushover analyses)

The event tree in Figure 4.3 uses the same principles as Figure 4.2: one of the possible hazards (H) results in a situation where there either is or is not an initial damage (D or $\overline{D}$) at a specific place (therefore many possibilities at the "D junction"). If there was an initial damage, the structure may or may not fail (F or $\overline{F}$). This latter two paths result in direct or direct + indirect consequences. This means that the given direct and indirect consequence(s) belong to a failure scenario. *Direct consequences* are considered as the direct result of the hazard exposure and, depending on the intensity of the exposure, may correspond to damage to one or more individual components. *Indirect consequences* in principle comprise all consequences in addition to the direct consequences.

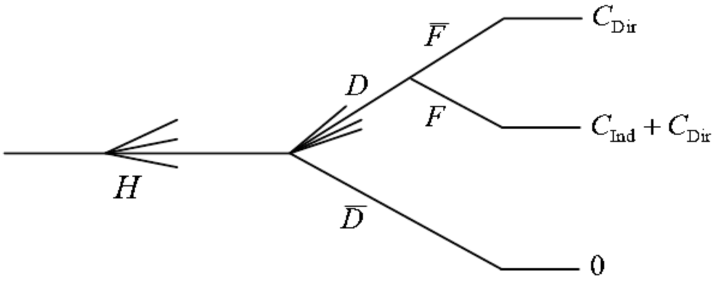


Figure 4.3: Event tree for quantifying robustness, source /33/

Formula 4.3 is the basis for risk analysis /33/:

$$R=\sum_i\sum_j C_{dir,ij}\,P(D_j|H_i)\,P(H_i)+\sum_k\sum_i\sum_j C_{ind,ijk}\,P(F_k|D_jH_i)\,P(D_j|H_i)\,P(H_i) \qquad \text{Formula 4.3}$$

In many ways, it is very similar to Formula 4.1, the additions are the following:

$C_{dir,ij}$	direct consequence of hazard *i* and initial damage *j*
$C_{ind,ijk}$	indirect consequence of failure *k*, hazard *i* and initial damage *j*
$P(F_k\|D_jH_i)$	probability of failure *k*, given hazard *i* and initial damage *j*
$P(D_j\|H_i)$	probability of initial damage *j*, given hazard *i*
$P(H_i)$	probability of hazard *i*

4.2.4.1 Creating indexes for robustness

Indexes for robustness (non-dimensional) are useful to compare different solutions and enable decisions based on these.

Risk based robustness index

The risk based robustness index is proposed by Baker et al. in /24/ uses the same division of direct and indirect consequences as above. The index of robustness is defined in Formula 4.4.

$$I_{rob}=\frac{R_{dir}}{R_{dir}+R_{ind}} \qquad \text{Formula 4.4}$$

R_{dir} and R_{ind} are the direct and indirect risks.

The index takes values between zero and one, with larger values indicating larger robustness. It is best used as an indicator to compare direct and indirect risk (i.e. propagation property), because considered that the goal is to minimize both direct and indirect risks, I_{rob} can have values very close to 1.0 with relatively large direct and small indirect risks

Reliability based robustness index

The following indexes are based on the works of Frangopol and Curley /34/ and Fu and Frangopol / 35/. The first one being the *redundancy index (IR)* in Formula 4.5.

$$RI=\frac{P_{f(damaged)}-P_{f(intact)}}{P_{f(intact)}}$$ Formula 4.5

$P_{f(damaged)}$ and $P_{f(intact)}$ are probability of failure for a damaged and intact system. The values of RI can be between 0 and ∞, the smaller values meaning more robustness (i.e. $P_{f(damaged)}$ is not much higher than $P_{f(intact)}$)

The second in Formula 4.6 is the *redundancy factor (β_R).*

$$\beta_R=\frac{\beta_{intact}}{\beta_{intact}-\beta_{damaged}}$$ Formula 4.6

In Formula 4.6 β_{intact} and $\beta_{damaged}$ are the reliability indexes of the intact and damaged system. The value of β_R changes between 1 and ∞, following the higher the more robust rule.

β as a reliability index is defined in Formula 4.7 where Φ is the cumulative normal distribution function and P(F) is the failure probability, Cavaco et al. /36/.

$$\beta=\Phi(1-P(F))^{-1}$$ Formula 4.7

Deterministic robustness indexes

Within the category of deterministic robustness indexes it is possible to distinguish between those that take a basis in a non-linear structural analysis and those that utilize linear methods. The first group contains the

- reserve strength ratio and the damaged reserve strength ratio (1)

The second group incorporates the

- stiffness based robustness indexes and the (2, 3)
- Eigen value based robustness indexes (3, 4)

1) The *reserve strength ratio (RSR)* proposed by Faber et al. in /24/ is defined in Formula 4.8.

$$RSR=\frac{R_c}{S_c}$$ Formula 4.8

Where R_c and S_c are the base shear capacity and design value in ULS, the Rc value coming from a pushover analysis. RSR can take values between 1 and ∞, where the bigger number denotes more unaccounted capacity.

To specify better the effect of losing one particular member (I) the RIF value *(damaged strength ratio)* is defined in Formula 4.9.

$$RIF_i = \frac{RSR_{fail,i}}{RSR_{intact}} \qquad \text{Formula 4.9}$$

Where $RSR_{fail,i}$ is the RSR value of the platform given that member *i* has failed. The RIF takes values between 0 and 1, with larger values indicating larger redundancy.

2) Robustness can be measured by using the determinant of the static stiffness matrix of the structural system /31/.

$$R_S = min \frac{det\, \mathbf{K_j}}{det\, \mathbf{K_0}} \qquad \text{Formula 4.10}$$

In Formula 4.10 R_s is the stiffness based robustness measure, $\mathbf{K}_0$ is the stiffness matrix of the intact structure, $\mathbf{K}_j$ is the stiffness matrix of the structure with the given member(s) removed. This expression needs further normalization in order for it to give a value between 0 and 1, as written in Haberland /37/.

3) Robustness can also be measured using the methodology proposed by Olmati et al. /38/ using the Eigen values of the static stiffness matrix.

There is a set of damage scenarios assumed, where the damage is represented with a consequence factor ($C_f^{scenario}$ in Formula 4.11). The damage scenario is defined as the loss of one or several members. Robustness is expressed as the complement of $C_f^{scenario}$. (Formula 4.12)

$$C_{max}^{scenario} = max\left(\frac{\lambda_f^{un} - \lambda_f^{dam}}{\lambda_f^{un}} 100\right)_{f=1..N} \qquad \text{Formula 4.11}$$

$$R_{scenario} = 100 - C_{max}^{scenario} \qquad \text{Formula 4.12}$$

The consequence factor and the robustness are expressed in %. The higher percentage of C means higher consequences and less robustness in the given failure scenario.

In the above formulas λ_f^{un} and λ_f^{dam} are the Eigen value number *f* of the stiffness matrix in the structure's intact and damaged condition.

This method has certain limitations:

- not fit for structures that have high concentrated masses (especially non-structural masses) in a particular zone, because the method does not take into account dynamics and masses

- not fit for structures that have cable structural system (e.g., tensile structures, suspension bridges), because of the geometrical non-linearity of cable structures. In these cases the stiffness matrix is a function of the loads (stress stiffening), something not accounted for in the elastic stiffness matrix, as well as other effects (e.g. catenary actions) cannot be taken into account this way.

4) A method based on 3) by Olmati is proposed with the following additions:

- the formulas used (Formula 4.11 and Formula 4.12) are kept with no changes, but λ_f^{un} and λ_f^{dam} are the undamped free vibration Eigen value number *f* of the structural system gained from Formula 4.13 to Formula 4.19.

$$[M]\{\ddot{x}\}+[K]\{x\}=0$$ Formula 4.13

$$\{x\}=\{X\}e^{i\omega t}$$ Formula 4.14

$$[-\omega^2[M]+[K]]\{X\}e^{i\omega t}=0$$ Formula 4.15

$$[[K]-\omega^2[M]]\{X\}=0$$ Formula 4.16

$$[M]^{-1}[K]=[A]$$ Formula 4.17

$$\lambda=\omega^2$$ Formula 4.18

$$[[A]-\lambda[I]]\{X\}=0$$ Formula 4.19

This method has the benefits of 3) but improves on the dynamic properties, since it takes into account the mass matrix, hence it is more fit for structures with concentrated masses. On the other hand it does not improve on the properties of the method in connection with structures that utilize cable systems. Stress stiffening can be accounted for in the free vibration analysis, but the results will be unreliable for highly non-linear structures.

A practical example, using this method has been created and documented in Appendix B, a summary of the results is included in section 4.4.

4.3 Using barriers for ensuring robustness

Ersdal in /39/ is using the barrier method to establish criteria for a robust design. The concept of the methodology is shown in Figure 4.4, which is a reproduction from Ersdal /40/. Structures have their operational envelope. This is the area of normal operation, and corresponds to where the design value of loads does not exceed the value that belongs to the annual probability of 10^{-2}. There are several reasons why the circumstances can be such that the structure steps out from its operational envelope. These can be extreme loads, accumulated deterioration effects, accidental situations. If the structure survives in these situations depends on how well the barriers are functioning.

Ersdal names 6 barriers that build up the robustness of a structural system which are denoted as the principles of safe design. These 6 principles are based on various standards (ISO 2394:1998, ISO/DIS 2394:2013, ISO 19900, EN 1990). The principles are the following:"

1. Knowing and controlling the hazardous events and actions
2. Limiting the structure's sensitivity to the hazardous events and actions
3. Ensuring that the structural elements are able to withstand the stresses from the hazards they are exposed to
4. Ensuring that a single structural element failure is visible or detectable prior to a complete collapse of the structure
5. Ensuring that the structure has the necessary damage tolerance
6. Reduction of the consequences of a collapse of the structure

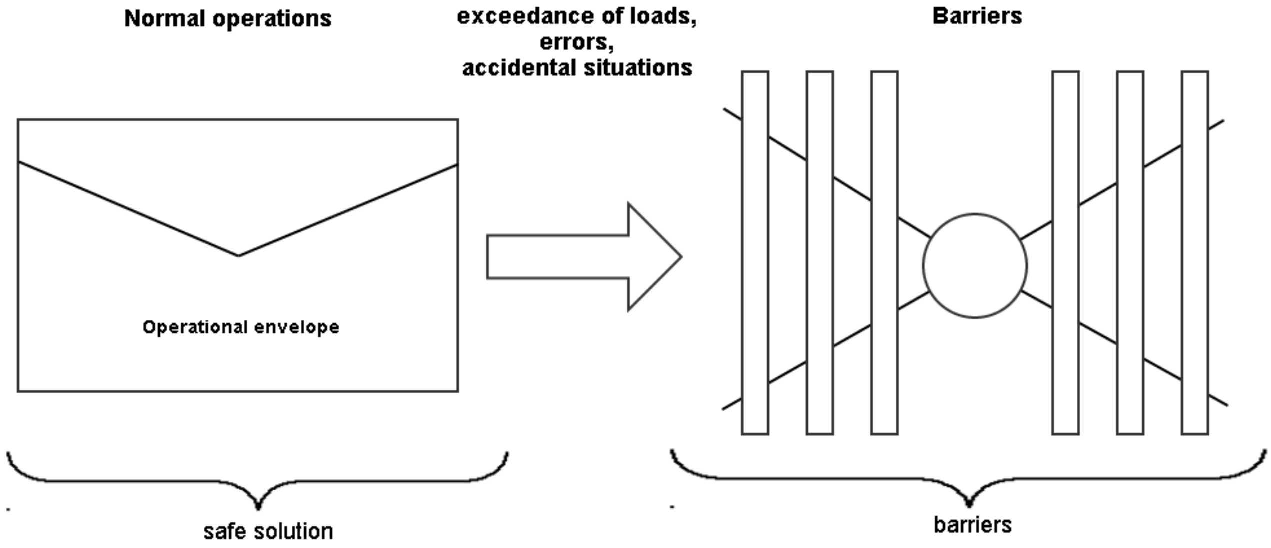


Figure 4.4: Operational envelope and barriers, based on /40/

The 6 principles or barriers of robustness are represented in Figure 4.5

Similarly to Aven, Ersdal defines robustness as the antonym of vulnerability, and assigns a broader context to robustness, expanding the meaning from "limiting consequences or stopping consequences from propagation" to including the avoidance of initial damage.

The definition that Ersdal gives in /39/ covers the whole equation of Formula 4.1, since Ersdal's barriers have influence on

- the probability of the hazard
- the initial damage given the hazard and
- the probability of failure/consequence given the initial damage

This way, Ersdal is able to incorporate the entire domain of design, maintenance and emergency preparedness.

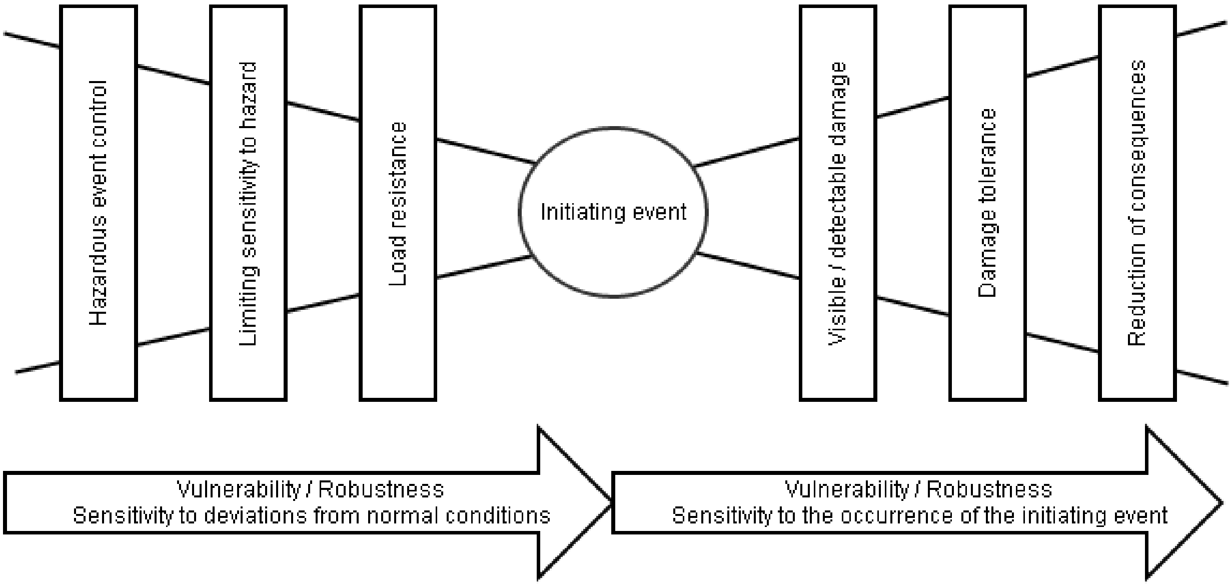


Figure 4.5: Six principles of safe design, source /39/

4.3.1 Application of barrier method

In this section, the focus is on the example of an offshore jacket structure. In this section I will bring examples on the barriers of Figure 4.5 in connection with these type of structures. It is not the goal of the thesis to provide a complete reference, but to show examples on typical structural related topics. The examples are excluding fire and explosion which are quite extensive topics on their own and are dealt with throughly in other works and within other disciplines.

4.3.1.1 Hazard: boat collision / iceberg collision

1) **Hazardous event control**: it is possible to monitor supply boats, other ships and icebergs, as well as use e.g. GPS based systems on ships; and apply alarms if the ship is on a collision course. This way possible to reduce P(H)

2) **Limiting sensitivity to hazard**: The sensitivity to this kind of hazard can be reduced by the use of non-structural members in a sense that these do not contribute to the integrity of the platform, but have enough energy absorbing capabilities. This way they can reduce the kinetic energy of the collision object by large deformation. This measure reduces P(D|H).

3) **Load resistance**: Structural members have to be designed for the proper accidental action (e.g. DNV-RP-C204 /41/), so that they suffer no damage from these actions with the defined annual return period. This measure also reduces P(D|H)

4) **Visible detectable damage**: The design has to be careful with creating connections that are stronger than the members, this way the damage appears at places that are easier to inspect. This measure reduces P(F|DH).

5) **Damage tolerance**: On the side of steel material properties and element design, adequate ductility has to be provided so that the suffered damage does not cause brittle failure. This way either a limited member capacity can be maintained, or the dynamic effect of load redistribution can be decreased. The provided ductility may make it possible for the element to carry loads in a different way than previously (e.g. catenary action after the formation of plastic hinges).

   On the side of structural system design, it has to be made possible that loads can be redistributed and alternative load-paths can be found. These measures reduce P(F|DH)

6) **Reducing consequences**: Make it possible to launch lifeboats in damaged / tilted condition. This measure also reduces P(F|DH).

4.3.1.2 Hazard: Extreme wave / Topside overload

1) **Hazardous event control**: With respect to topside weight, it is possible to have a change management system (e.g a SIM system), this way keeping track of changes and applying assessment if the appropriate assessment triggers are activated.

   The annual probabilities of extreme waves are based on statistics. Regular update of statistical data can reveal a design that will under-perform in this design scenario.

2) **Limiting sensitivity to hazard**: It can be a design approach of topside structures to limit the eventual P-Δ effects occurring in a scenario with sideways extreme loading.

   The provision of adequate air-gap prevents the wave-loading of the deck (larger exposed area with higher solidity than for the jacket).

   Reducing the number of conductors limits the forces the structure is exposed to.

   Similar is the effect with the removal of marine growth (i.e. force reduction).

   A non-structural but effective counter sensitivity measure can be to limit where personnel can be during storm.

3) **Load resistance**: Appropriate ULS/ALS design of the structure.
4) **Visible detectable damage**: as in 4.3.1.1
5) **Damage tolerance**: as in 4.3.1.1
6) **Reducing consequences**: Evacuate personnel before storm, make it possible to launch lifeboats in damaged / tilted condition.

4.3.1.3 Hazard: Fatigue / Corrosion

1) **Hazardous event control**: this type of hazard can be controlled by inspections, which reduce the possibility of undetected degradation. When it comes to corrosion, the application of consumables of cathodic protection can be a solution.
2) **Limiting sensitivity to hazard**: the proper design solutions can result in more favorable SN-curves and reduced hot-spot stresses.
3) **Load resistance**: appropriate FLS design of the structure, quality check of fabrication. It is an experience that fatigue calculations are very conservative, but fabrication defects dramatically reduce fatigue life at unexpected locations.
4) **Visible detectable damage**: design solutions can ensure that fatigue cracks appear on detectable sides of the welds
5) **Damage tolerance**: a possibility to limit the sensitivity for fatigue and corrosion is applying design solutions with redundancy, i.e. the loss of one member does not lead to the collapse of the structure. E.g. bracing types can contribute to such behavior
6) **Reducing consequences**: as in 4.3.1.1

4.4 Summary of member consequence calculation

In Appendix B an example calculation is performed using the method 4) among the deterministic robustness indexes in section 4.2.4.1. The results and conclusions are summarized in this section.

The main formula used is Formula 4.20. Where λ_f^{un} and λ_f^{dam} are the undamped free vibration Eigen value number *f* of the structural system.

$$C_{max}^{scenario} = max\left(\frac{\lambda_f^{un} - \lambda_f^{dam}}{\lambda_f^{un}} 100\right)_{f=1..N} \qquad \text{Formula 4.20}$$

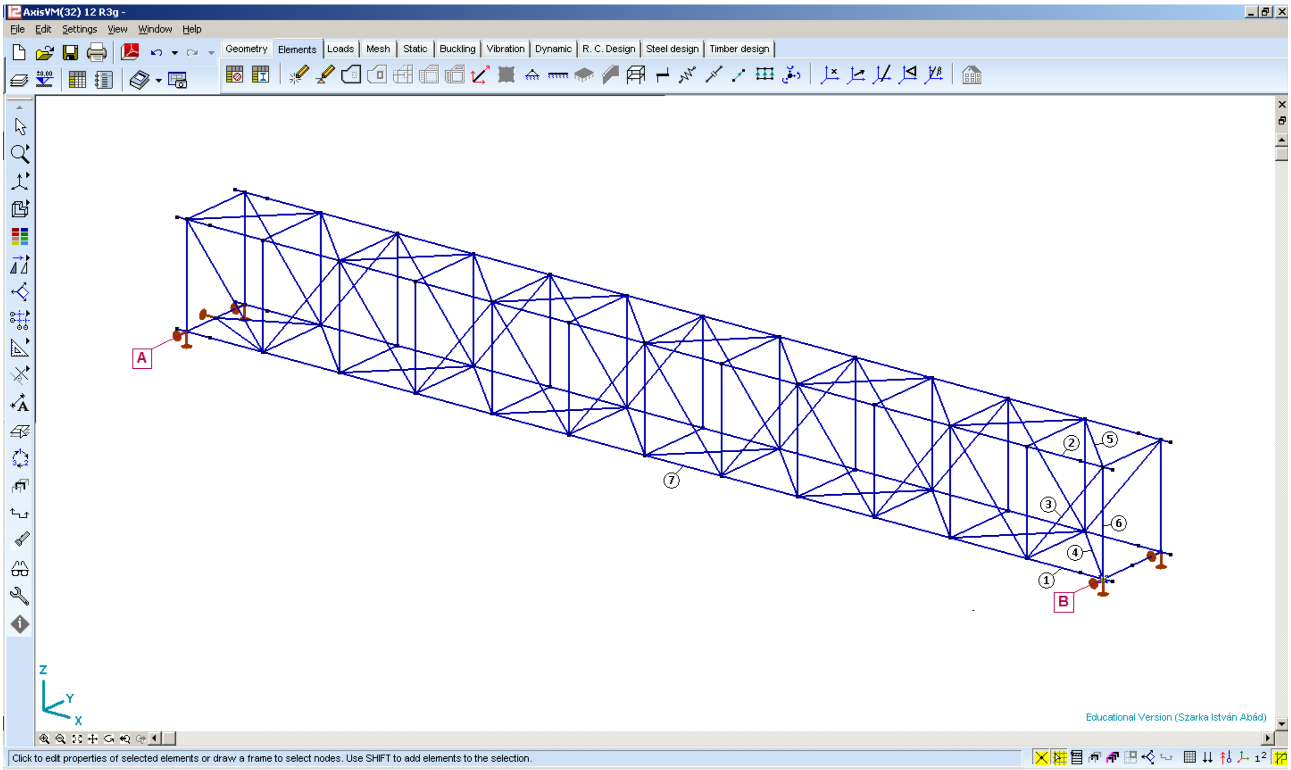
It has to be noted about this method that it does not provide a global robustness index or factor as the RSR value for an intact structure. This method is more focused on member importance, or the consequence of losing a particular member or members.

There has been a bridge structure (Figure 4.6) used to test the methodology. Several members were removed from the structure (only one at a time) in an attempt to assess the consequence index that belongs to the individual members. In Table 4.1 a summary of the results is provided.

Table 4.1: Summary of results using proposed methodology

Member	**Consequence (C_f)**	**Critical Eigen mode**
01 – Lower chord at support	40%	3
02 – Upper chord at support	33%	11
03 – Main diagonal (vertical) at support	26%	11
04 – Lower diagonal (horizontal) at support	33%	11
05 – Upper diagonal (horizontal) at support	34%	11
06 – Column above support	35%	11
07 – Lower chord at mid-span	49%	1

The results show that many members have their most critical Eigen mode as no. 11. and the consequence is very often close to 30-35% with quite small variation. This is somewhat unexpected.



Click to edit properties of selected elements or draw a frame to select nodes. Use SHIFT to add elements to the selection.

Figure 4.6: Test bridge with members selected for consequence evaluation

<u>*Group of chord members:*</u> It is member 01, 02 and 07 that belong to this group. Member 01 and 07 have the highest consequence among all the investigated members in Table 4.1. From beam theory it is susceptible that member 07 should have a high consequence, but it is unlikely that member 01

has a consequence that is very close to member 07. It is even more unlikely that member 02 has a lower consequence than member 01. The reason for this is: if the elevation view is looked at and we imagine removing member 01, there is still a stiff, supported triangle transferring vertical forces to the top of the column, on the other hand if member 02 is removed the stiff triangle at the support becomes a bit “mechanism-like” in its connection to the main vertical girder of the bridge.

Diagonals: It is worth noting that vertical diagonal has a lower consequence than the horizontals, as well as that there is no significant difference between the lower and upper diagonal. This latter seems unlikely because the loads will have to be transferred anyways to the supports at the lower points, so losing the lower horizontal diagonal is probably of higher consequence.

Arguments in favor of the method (pros):

- Easy to perform the analysis
- Can be performed in the vast majority of structural FEM software
- Low on computational resources

Arguments against the method (cons):

- the results seem to contradict the engineering gut feeling about the consequence of the members
- the results are not load specific: many structures are specifically designed for loads from a certain direction that is usually dimensioning (e.g. beam bridge for vertical loads)

In summary, it can be said that the methodology failed to deliver to the expectations.

A closer look however to the results revealed some correlation between a slightly modified consequence index and an assumable real consequence.

It is mentioned above among the cons of the methodology that it is not load specific, more closely, not specific to the direction of the load. The methodology has been modified in a way that the consequence factor is not generated from the maximum deviation from all the considered Eigen values, but it is taken using only the Eigen mode the modeshape of which resembles most the assumed deflection curve of the structure for the given load.

The structural model has been modified in a way that a loadcase with vertical loads has been created. In connection with this the second Eigen mode has been selected. The structure has been code-checked using Eurocode 3 /42/ rules in intact condition and after individually removing the selected members shown in Figure 4.6. The loads on the intact structure were scaled in a way that the highest code-check result is 0.8 in the structure.

From the gained code-check results two indexes were taken: the gained maximum code-check result or utilization factor (Uf_{max}) from the whole structure; and the biggest change in utilization (Δ) among all the members. The first index (Uf_{max}) is used to assess how big the consequence was from removing a member, the second (Δ) can give a hint about how extensive was the force redistribution in the structure. The results are summarized in Table 4.2.

Table 4.2: Summary of code-check results

Intact Model	Removed member													
	01		02		03		04		05		06		07	
UF_{max}	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ
0.80	0.80	0.05	1.69	1.60	1.44	1.25	0.80	0.05	0.80	0.01	1.56	1.40	2.16	1.39

In Figure 4.7:

- UF is the utilization factor (Uf_{max}) from Table 4.2, <u>the values are scaled</u>
- Δ from Table 4.2, <u>the values are scaled</u>
- C-1 is the consequence according to Formula 4.20, with the modification that is is not the maximum difference chosen from all the Eigen values, but it is the difference in Eigen value no.1. The first Eigen mode is a horizontal bending mode (Figure 2.6).
- C-2, similar to C-1, but it is Eigen mode no.2 from which the Eigen values are taken. This mode is a vertical bending and the shape resembles very much to the expected deformation plot from gravity or vertical live loads (negative).
- C-max is the consequence according to Formula 4.20, the results are from Table 4.1.

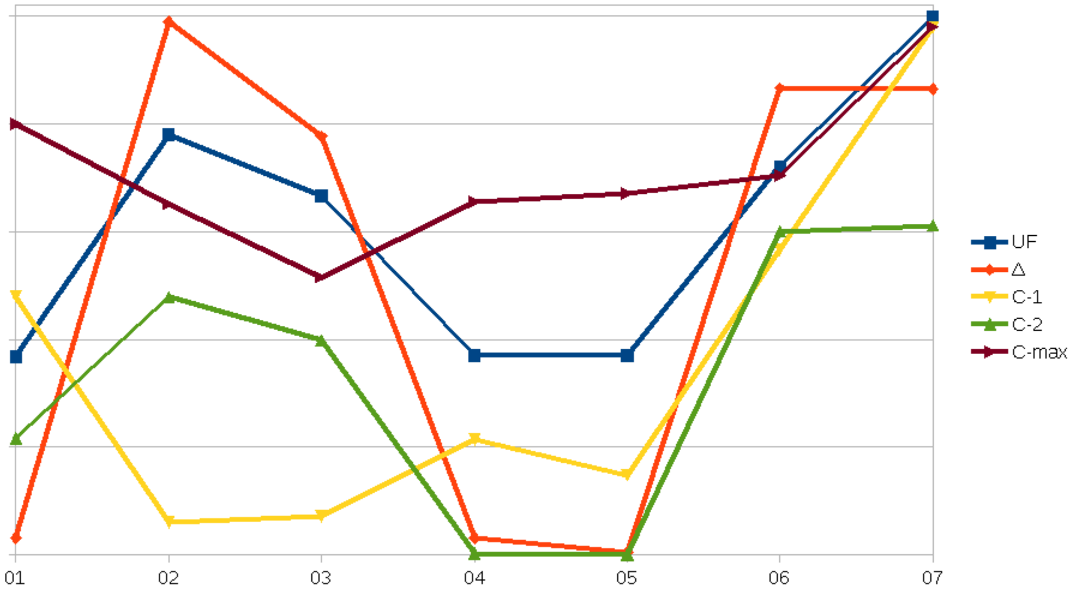


Figure 4.7: Result summary of the modified methodology

The Figure 4.7 was created to highlight the correlation between UF and C-2, and also between Δ and C-2. There is a strong positive correlation for all members (except 07) between UF and C-2. The correlation is even stronger between Δ and C-2.

It is also worth looking at the line of C-1 which belongs to the first horizontal bending mode. There seems to be a negative correlation with UF at member 04 and 05. It seems reasonable that the consequence of horizontal braces (04, 05) is higher in a mode with horizontal bending. The results also match the gut-feeling that member 04 should have higher consequence (lower brace).

Compared to the original methodology (method 4) among the deterministic indexes in 4.2.4.1), it is an improvement that there seems to be a way to become more load specific, or directional.

In spite of the visible correlation in the modified methodology, there should be done many tests and analyses to be able to verify and prove, or contradict the method's reliability, furthermore:

1) Consequence values should be compared to push-over analysis results, with non-linearities taken into account
2) It should be investigated how results are affected by structures that include high concentrated masses.
3) It should be looked at how the involved mass in each Eigen mode is in connection with the results – e.g. consequence index can have more or less relevance if participating mass is high or low, totally or in a given direction.
4) It should be investigated if the consequence index in Formula 4.20 can reveal something about the structure in connection with loads that were not accounted for.

5 Discussion and summary

Structural Integrity Management has been brought to life by need to be able to document adequate likelihood of structural integrity of critical structures. These structures are typically of high value, operated in an environment which are known to be damaging, are exposed to corrosion. Their failure can be catastrophic for the society and the environment, and it may have significant financial impact. The above factors were known and accounted for in the design phase for a given design life. With new technologies emerging in hydrocarbon recovery, there appeared a need to operate these structures longer as well as to modify them to suit the changed needs. Also the loss of knowledge about the facilities could be experienced because of leaving personnel and companies going out of business. This resulted in a growing uncertainty if fit-for-purpose condition can be maintained.

It was an objective of this thesis to find out if Structural Integrity Management, as it is described in API RP2SIM /1/, ISO19902 /2/ and NORSOK N-005 /3/, can provide a system that ensures the maintenance of structural safety.

All three standards specify a framework that elaborately defines what is to be done by the facility operators to have reliable assets, to be aware of the shortcomings in their facilities and to mitigate the risk connected. All three define SIM as a cyclic process, and have rather similar understanding of the four elements of the cycle: data, evaluation, inspection plan, inspection execution.

The SIM system is tailored for managing change, because it integrates storing information about the change, it initiates its evaluation and it takes a proactive approach in finding changes (inspections). This is the main priority in ensuring a fit-for-purpose condition. All three standards take the baseline inspection as the starting point and continuously store, process and initiate reaction to changes, so that the emerging risk is mitigated. On the other hand it can be noted that there are additional things that could have more focus in a SIM framework:

- If Figure 3.5 and Figure 3.6 is looked at in the section of Barrier concept, it can be seen that the establishment of barriers is part of a bigger picture. The outer loop is responsible for ensuring that barriers are kept up-to-date. A similar “improvement loop” for SIM has almost no focus in API RP2SIM. An established SIM system, as all systems, degrade with time. It would be important to emphasize, as it is included in NORSOK N-005 (Figure 2.7), that the processes, formed by the four main blocks of SIM, need continuous re-evaluation and improvement.
- SIM processes are very much based on engineering evaluation. Engineering decisions are made in every cycle on the impact, criticality or uncertainty of a finding or change. Additionally, the assessment parts require extensive engineering skills. Ensuring that engineers involved in the SIM process are adequately knowledgeable on structures, as well as they are aware of the differences between design and assessment engineering, is an important factor in effective structural integrity management. There is limited requirement

in SIM standards in connection with this. Ensured skills could be connected to formal requirements, years of experience or other qualities.

It was also the objective of this thesis to explore what role DNV GL's SIMS software has in the process of integrity management of structures.

The SIMS software product is developed by DNV GL Software. It is a supporting tool for the SIM process. Its purpose is to provide and aid for executing the four main SIM principles. It is a solution that presents a background for inspection and assessment activities in the same environment. Numerical assessments are carried out in programs outside of SIMS. This is true for the actual generation of inspection intervals/programs also. The results of analyses are registered in SIMS through the use of analysis statuses, and the prescribed inspections find their way into the system through the creation of work packages and campaigns. The SIMS system is very good at showing high level summaries, but also the hierarchic breakdown of structures and facilities is very elaborate and detailed. The SIMS system fully supports all intended activities, as well as it features additional elements that ease the activities (e.g. 3D viewer).

A third objective was to evaluate if barriers are part of the SIM process and if SIM standards recognize this or not.

There is almost nothing about barriers in the API RP2SIM /1/ and in ISO19902 /2/, but the proposed new version of NORSOK N-005 /3/ has more focus on barriers. The beginning of N-005 states “These provisions of this standard are based on the rational method of managing safety-critical systems, activities and elements (barriers), (…). This includes the principles and strategies for establishing and maintaining barriers so that their function is safeguarded throughout the life of a facility.” /3, section 1/.

Barriers are a part of SIM because, as the N-005 states, “the objective of integrity management of structures and marine systems is to ensure and document an acceptable level of safety and suitability for their intended purpose in all phases of their life” /3, section 4.1/. I.e. both suitability and safety of the structures have to be ensured. Barriers are the means to ensure safety for personnel, environment and assets. The barrier methodology is very suitable for identifying hazards and control strategies for hazards. It enables analytical risk control. Its application builds up a defense in depth safety ensuring structure.

The fourth objective concerned the connection between robustness and SIMS.

As it was shown in section 4, there can be given many definitions for robustness ranging from a purely structural to a system concept. Most of the system concept definitions agree on that a system can function well without being robust, and robustness is a property that comes to the foreground in the event of the extreme, when the situation is outside the operational envelope. Robustness is about surviving the unforeseen. Robustness with a focus on structural properties tries to measure the unaccounted capacity, the risk connected to a collapse, the reliability of the structure. Other structural robustness indexes often express the consequence of losing one member.

The system view concepts of robustness have the advantage over purely structural robustness definitions that the protection of humans, environment and assets is not just an indirect outcome of structural survival. It is robustness defined with the barrier method that gives the most complete picture, in this respect, from a structural safety point of view. It is the robustness achieved through the layered defense mechanism that is the most suitable to mitigate risk arising from a multitude of hazard sources in a number of accident scenarios, and which can accommodate the various consequence reduction methods. If robustness is defined with the barrier method, then the structure is not separated from the processes that take place on it or the environment it is part of.

Robustness is desirable property in Structural Integrity Management because of the its purpose. Namely to ensure the structure's safety and suitability. This means that it is a requirement in SIM to maintain robustness. The NORSOK N-005 /3/ makes this connection between SIM, barriers and robustness, but it is missing from the API and ISO standards.

The fifth objective is to investigate how Structural Integrity Management processes can contribute to maintaining robustness and barriers.

The SIM process starts after fabrication, after commissioning with a baseline inspection or in a different time close to installation. This results in that the SIM process does not have the possibilities to implement barriers that would ensure robustness the same way as the design process has. Those who work with the SIM process has to take a finished structure in the condition that it is in as a starting point for their work. Therefore it is more focused in the SIM process to maintain the built-in robustness than to implement new ones. However, it can be part of the SIM process to evaluate the in-service barriers and to alter functions, adjust performance standards of barrier elements. The SIM process contributes to ensuring initial robustness and maintaining barrier functions because:

- the purpose of SIM is to maintain fit-for-purpose condition with respect to safety and suitability. This is usually the closest possible to the intended design condition. Unless changes in regulatory requirements make it necessary to deviate from design intentions, reparations on the structure are aimed to reinstate a close-to-design state.
- the SIM process contributes also because its intention is to have updated knowledge on the real as-is condition of the structure (inspections, surveillance), as well as it continuously documents its regulatory compliance status (change management). Structures degrade over time in a pace that reparations usually cannot keep up with. Applying SIM procedures results in awareness of ill conditioned parts, or issues that increase the risk connected to platform operation. The updated knowledge enables risk mitigation and informs the operator about where barriers have fails.
- the SIM process builds a background knowledge database for improvements. I.e. all future improvements have a solid basis due to the available information on structure history.

5.1 Possibilities for further studies

Further studies could be conducted in connection with the consequence index calculation in Appendix B in order to verify or reject the engineering use of the methods described.

In connection with robustness, barriers and Structural Integrity Management, it could be a subject of further investigation how the three topics could be made more apparently connected.

In the course of establishing barrier strategy and performance criteria, the hazards and the corresponding barriers are precisely identified. Surveillances and findings concern a specific barrier or barriers. Each critical and unmitigated finding weakens the barrier(s) that it belongs to. The system of barriers can be established either according to Figure 4.5 or in a custom defined environment of safety principles.

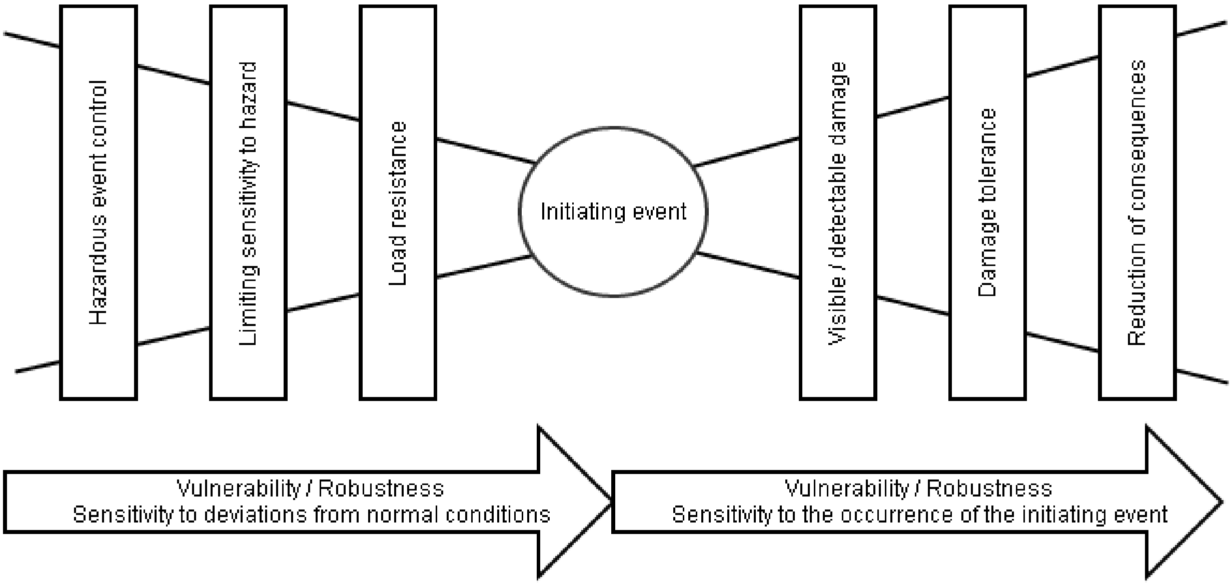


Figure 4.5: Six principles of safe design, source /39/ (repeated)

A study could be performed to find out if it is possible and practically viable to connect findings to barriers, this way creating a system where barrier status is constantly updated and trended.

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Appendix A

Evaluation considerations for inspection strategy

The following table is based on ISO19902 /2/

Table A1 Factors to be considered in the Evaluation process of structural integrity management

Considerations and factors
Structure age, condition, original design situations and criteria and comparison with current design situations and criteria • Remaining service life, desire to extend service life • Platform operating and maintenance personnel should be consulted to see if they have observed conditions (corrosion evidence, movement in conductor guides or riser/J-tube/caisson supports, excessive deformations or deflections, unusual vibrations, change in platform sway response to waves, etc.) that should be evaluated
Analysis results and assumptions for original design or subsequent assessments • Computed utilizations and fatigue lives • Original design code and version • Degree of sophistication and conservatism in the design analyses • Amount of conservatism in design implementation, acceptance criteria • Intentional over-design for fatigue to reduce periodic inspection requirements • Material specification
Structure reserve strength and structural redundancy
Fatigue sensitivity
Degree of conservatism or uncertainty in specified environmental conditions • Data source • Degree of certainty or conservatism in environmental conditions (wave, current, wind) and design assumptions (marine growth, earthquake spectra) • Sensitivity of storm actions to return period. For example, how much difference in magnitude of actions is there between the 10 year, 100 year, and 1 000 year events? • Relative severity of sea states for fatigue and storm conditions, since fatigue tends to be important where operational sea states are not far below design storm conditions • Marine growth type (hard, soft), percent coverage, thickness, variation with depth, roughness
Extent of inspection during fabrication and after transportation and installation
Fabrication quality and occurrences of any rework or re-welding • Unusual or special circumstances, rework/re-welding, wind induced vibrations/fatigue • Extent of inspection during fabrication Fabrication quality • Welding procedures and specifications
Damage (including fatigue damage) during transportation or installation • Occurrence of any damage or vibrations during transportation • Extent of inspection after transportation • Severity of transport conditions and actual exposure (for example transoceanic versus local tow) • Occurrence of any damage during installation Extent of inspection after installation

• Extent of deviations from design assumptions (e.g. air gap between deck and mean sea level)
Operational experience, including previous in-service inspection results and lessons from performance of other structures • Degree of vigilance in reporting/evaluating accidental events. • Extent of deviations from design assumptions (e.g. sea states, marine growth, platform purpose) • Modifications and additions of risers, service caissons, topsides, etc. • Occurrence of any damage • Absolute years of service • Years of service relative to design service life • Subsidence • Scope of prior inspections • Tools and techniques used • Anomalies discovered • Trends identified • Failures or problems encountered with certain components under certain conditions • Success of similar structures in same locale/region
Modifications, additions and repairs or strengthening • Underlying causes necessitating repair or strengthening In-service performance of repairs or strengthening
Occurrence of accidental and severe environmental events
Criticality of structure to other operations
Structure location (geographical area, water depth) • Particular regional experience
Debris
Structural monitoring data, if available
Potential reuse or removal intents

Appendix B

Consequence and Robustness factor

Table of Contents

Illustration Index

Index of Tables

B1 Introduction

This Appendix documents the calculations performed to test the consequence and robustness factor which are based on Olmati et al. /1/ including the modifications described in the main part of the thesis in Section 4.2.4.1 part 4).

In this method the consequence and robustness factors are based on the Eigen values of the free vibration modes of the structure in intact and damaged condition.

The structure subject to the analyses is an offshore bridge. No geometry, sections or other properties were directly used from real life structures, but the B01 and B02 bridges of the Ekofisk M platform served as a pattern and inspiration.

B2 Analysis software

The presented analyses have been performed using the educational version of AxisVM (32) 13 R3g which is the product of InterCAD Ltd.

The developer company introduces AxisVM as "Civil engineers on 5 continents use AxisVM for the analysis of structures with confidence that their final engineering product will meet the most up-to-date engineering analysis and design requirements. For nearly 25 years, AxisVM has been recognized as the industry standard for Building Analysis and Design Software.

Today, continuing in the same tradition, AxisVM has evolved into a completely integrated building analysis and design environment. The system built around a physical object based graphical user interface, powered by targeted new special purpose algorithms for analysis and design, with interfaces for drafting and manufacturing, is redefining standards of integration, productivity and technical innovation.

Structural analysis software that is intuitive and graphically driven so it is exceptionally easy to use and truly easy to start.

Available Languages: English, French, German, Dutch, Czech, Romanian, Slovak, Hungarian, Spanish, Italian, Serbian, Polish, Bulgarian, Portuguese.

Linear, nonlinear, buckling, vibration, seismic and dynamic analysis for truss, beam, rib, membrane, plate and shell two dimension and three dimension structures. Pushover and time history analysis. Code checking and design modules for steel, concrete and timber materials. Eurocode Design: EN1990, EN1991, EN1992, EN1993, EN1995, EN1997, EN1998 Import/Export to DXF, IFC, SDNF, ASCII, STL file formats and many others. Direct exchange with Tekla Structures. Dynamic report maker with image and table captures automatically updated with model changes." /2/

B2.1 Solving the free vibration problem

The Eigen values, frequencies and mode shapes are calculated for an undamped, linear system. In the used solver, no stress stiffening is taken into account, i.e. the stiffening effect of axial tension of the truss members is not accounted for.

In the calculations a diagonal mass matrix was used, this being sufficient because it is the global response of the bridge that is of interest and the structure consists of enough nodes and members.

B3 Model description

B3.1 Geometry

As shown in Figure 3.1, Figure 3.2 and Figure 3.3 the bridge is a space truss with a square bridge cross section, with a length of 48m (12x4m), a width of 4m and a height of 5m.

The bridge has a symmetric geometry, except for that the lower bracing accommodates to the pinned longitudinal support at the "A" raster at the middle of the width of the bridge.

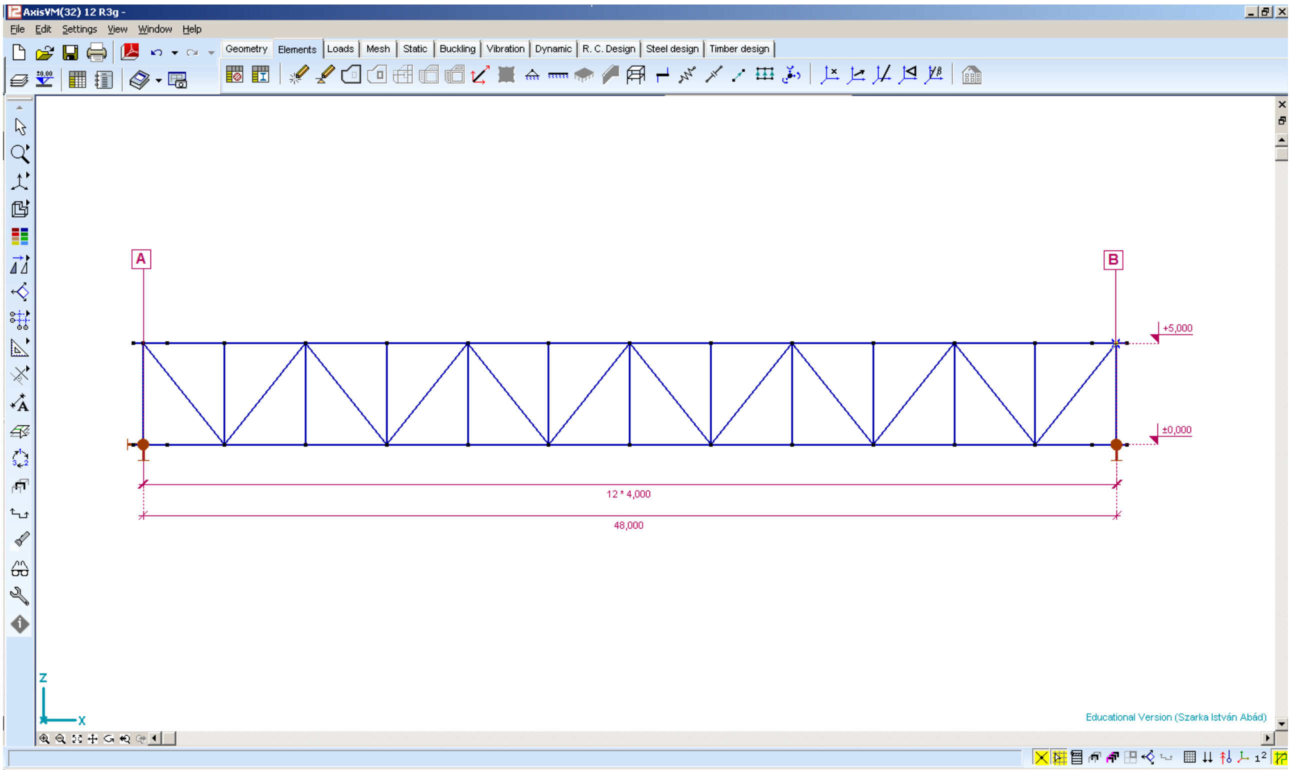


Figure 3.1: Geometry - Elevation

B3.2 Boundary conditions

All the boundary conditions are moment released, i.e. all the supports are pinned. At the "A" raster, the two supports at the sides can take up loads in the vertical (Z) and horizontal (Y only) direction, while the support in the middle provides constrain in the longitudinal (X) direction of the bridge.

At the "B" raster the two supports at the sides give a fixity in the global vertical (Z) and bridge lateral (Y) direction.

B3.3 Materials

Only one type of material (steel) has been used in the modeling, since the performed calculations (Eigen value analysis of a free vibration problem) only require the E modulus (2.1 x 10^{11} Pa), the material density (7850 kg/m^3) and the cross section properties of the used beam profiles.

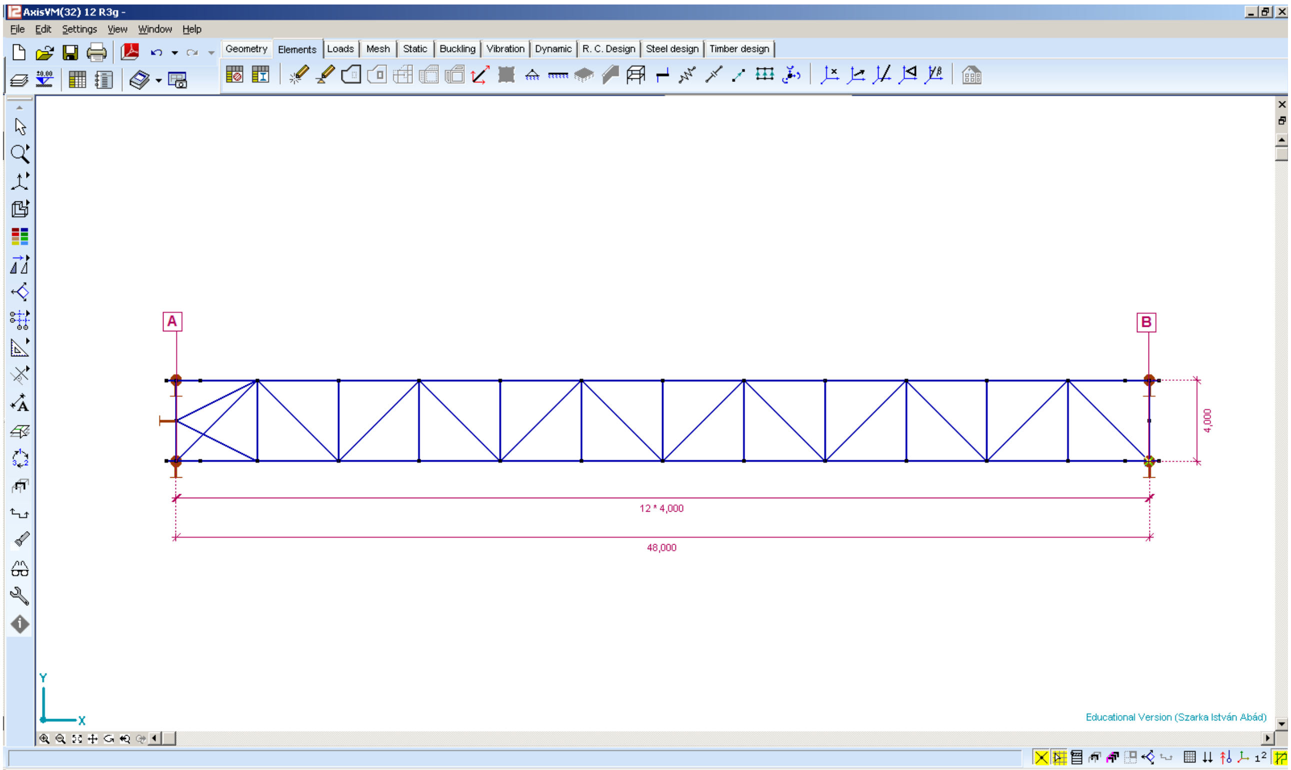


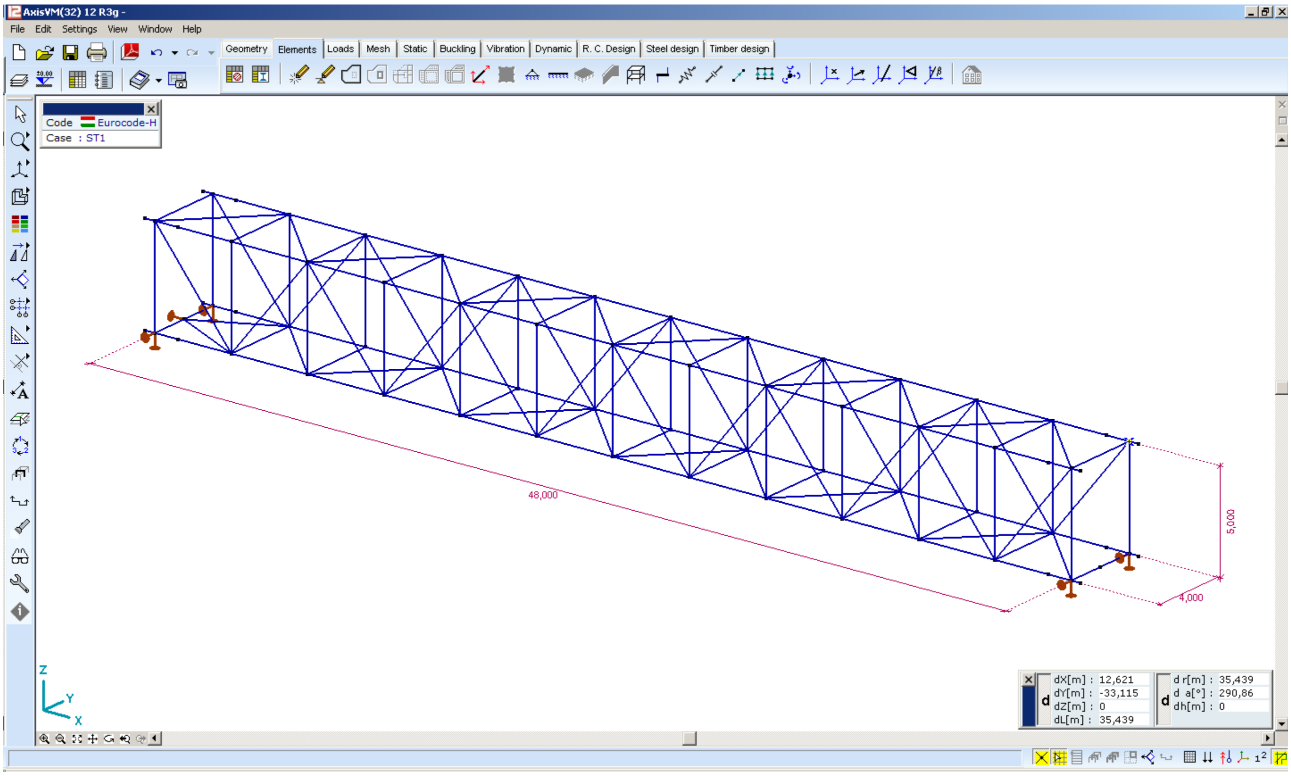
Figure 3.2: Geometry - Plan view – Upper and lower bracing is shown

B3.4 Sections

As shown in Figure 3.4 the bridge is built-up mainly of tubular sections, with box section reinforcements at the supports. There are also box sections (RHS) used for the lower and upper cross beams. The OD in the cross section name stands for outer diameter. The thickness in mm is the second number in the section name.

The main chord sections are OD300x10, with some reinforcement (OD350x16) where connection makes with the box sections make it necessary at the ends.

The diagonals for the vertical loads are OD160x10, except for the last tension and compression diagonal which are OD200x12.

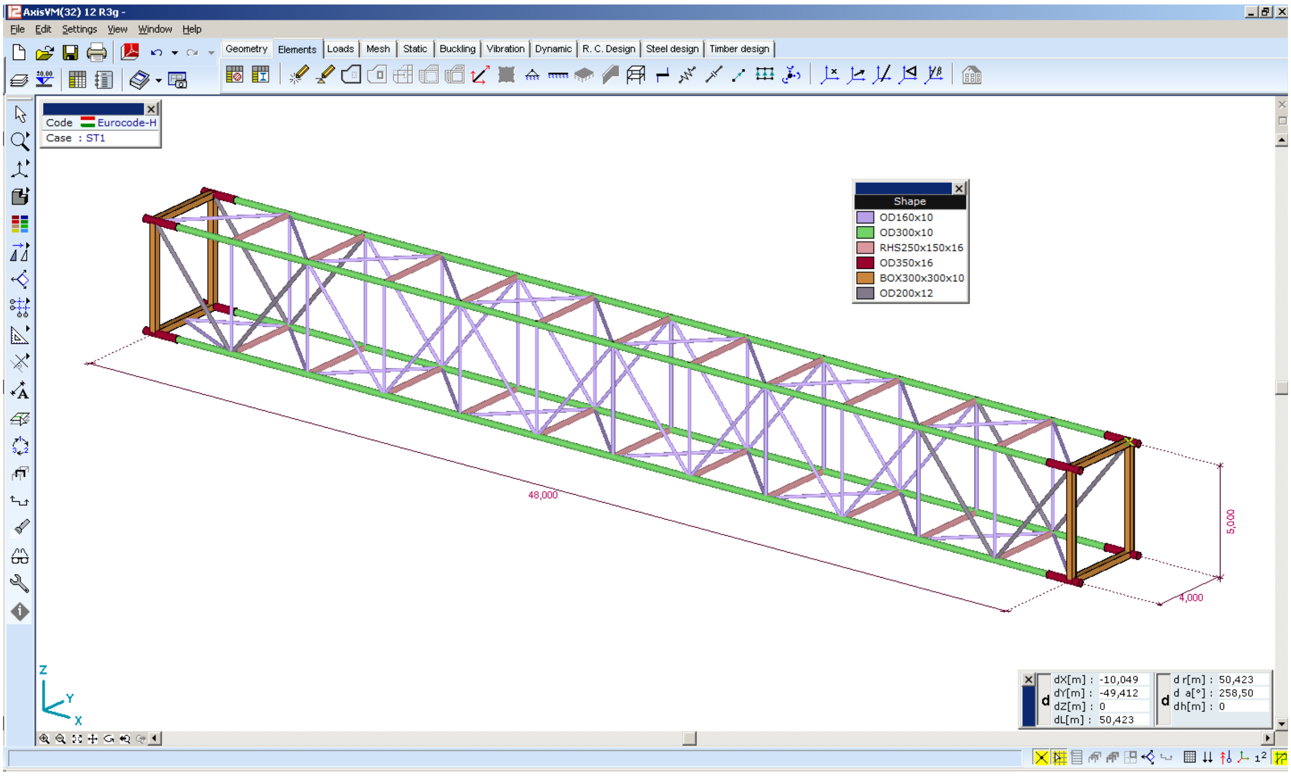


Code : Eurocode-H
Case : ST1

dX[m] : 12,621
dY[m] : -33,115
dZ[m] : 0
dL[m] : 35,439

d r[m] : 35,439
d a[°] : 290,86
dh[m] : 0

Figure 3.3: Geometry - Isometric view



Code : Eurocode-H
Case : ST1

Shape
- 🟪 OD160x10
- 🟩 OD300x10
- 🟥 RHS250x150x16
- 🟥 OD350x16
- 🟧 BOX300x300x10
- ⬛ OD200x12

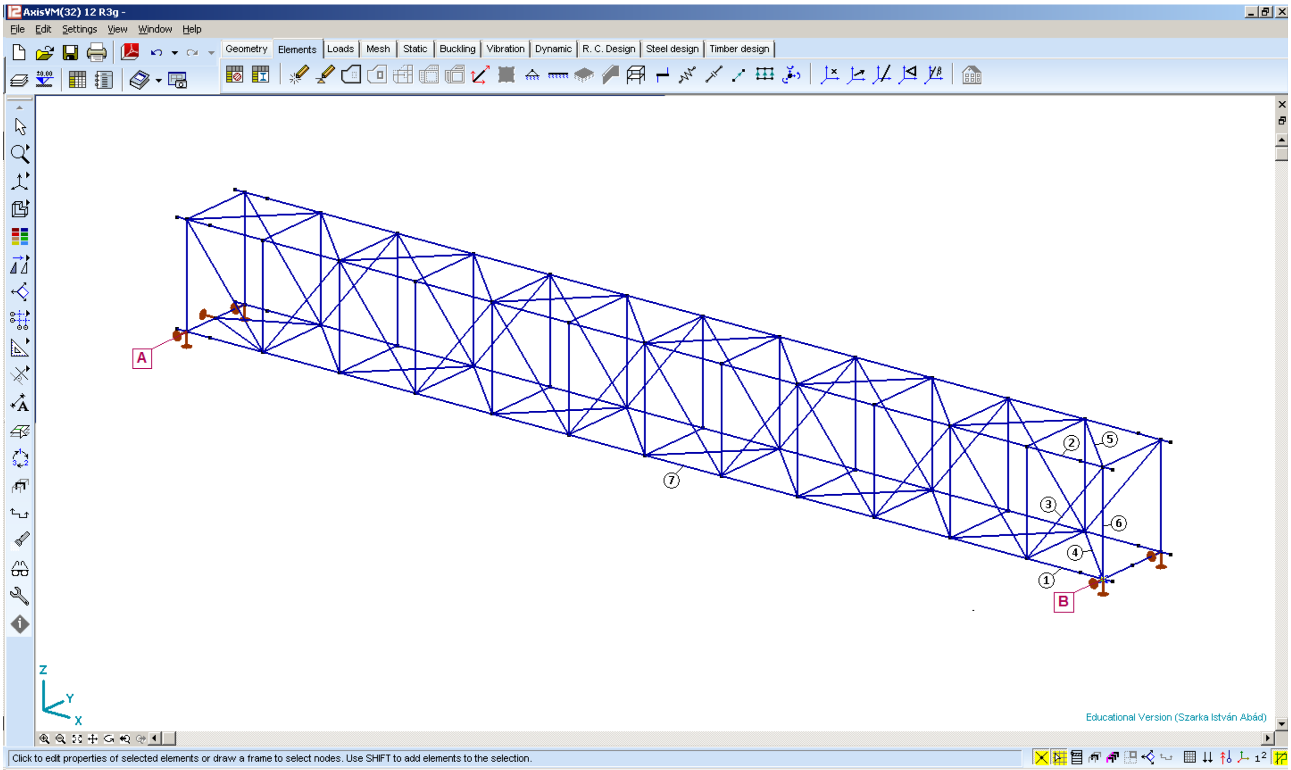
dX[m] : -10,049
dY[m] : -49,412
dZ[m] : 0
dL[m] : 50,423

d r[m] : 50,423
d a[°] : 258,50
dh[m] : 0

Figure 3.4: Beam cross sections - Color coded

B3.5 Damaged members

In Figure 3.5 the members that will be removed one-by-one from the structure are marked with numbers. There are six various members near the “B” end, and one chord member close to mid-span. These members are assumed to be damaged, and hence non-load bearing. It is only one member at a time that is removed from the intact/undamaged model, this way the subsequent analyses are member importance analyses, of a certain sort.



Click to edit properties of selected elements or draw a frame to select nodes. Use SHIFT to add elements to the selection.

Figure 3.5: Members denoting the damaged models

Member 1: Lower chord at the “B” end, above support

Member 2: Upper chord at the “B” end, above support

Member 3: Main vertical diagonal at the “B” end

Member 4: Main lower diagonal for horizontal loads at the “B” end

Member 5: Main upper diagonal for horizontal loads at the “B” end

Member 6: Main vertical (column) above support at the “B” end

Member 7: Lower chord member close to mid-span.

B4 Free vibration results for the intact model

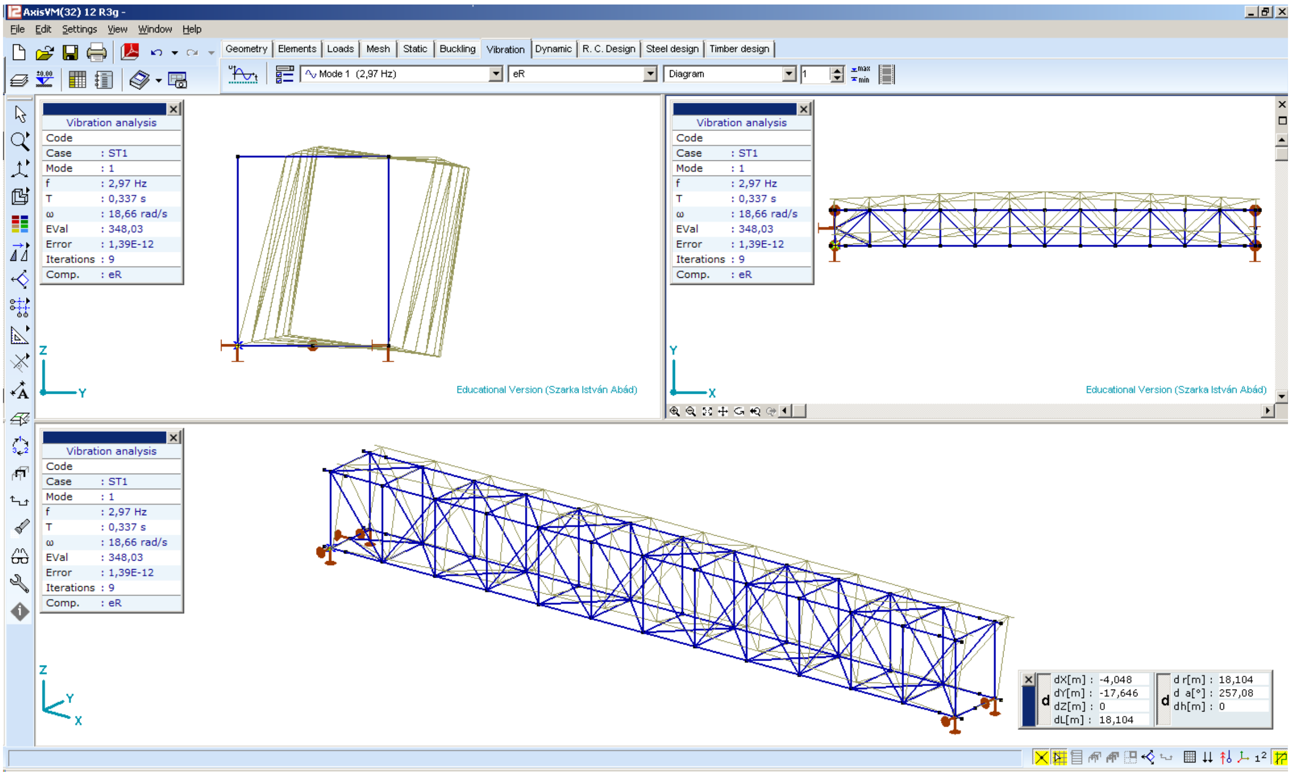
In Table 4.1 and from Figure 4.1 to Figure 4.10 the results of the free vibration analysis is shown. There are 25 Eigen modes computed which range from 2.97 Hz to 45.32 Hz (the first 11 is included in the figures below)

Table 4.1: Results of the free vibration analysis – Intact / Undamaged model

No	f [Hz]	T [s]	omega*	Eval (λ^{un})	Error
1	2.97	0.34	18.66	348.03	2.46E-12
2	4.66	0.22	29.26	856.16	3.86E-13
3	6.02	0.17	37.83	1431.38	7.69E-13
4	6.57	0.15	41.27	1703.51	5.52E-13
5	8.43	0.12	52.95	2803.21	1.90E-13
6	10.98	0.09	68.97	4757.04	2.66E-13
7	13.09	0.08	82.24	6762.85	6.89E-14
8	13.35	0.08	83.85	7031.05	2.20E-13
9	15.1	0.07	94.9	9006.01	3.48E-14
10	15.57	0.06	97.83	9571.01	1.11E-13
11	21.91	0.05	137.65	18948.11	4.69E-14
12	22.2	0.05	139.47	19452.21	2.42E-14
13	24.56	0.04	154.28	23803.57	3.93E-14
14	25.08	0.04	157.56	24825.58	2.58E-14
15	30.09	0.03	189.03	35734.13	1.16E-12
16	31.51	0.03	197.95	39184.9	2.95E-12
17	33.25	0.03	208.89	43635.05	4.34E-11
18	33.94	0.03	213.28	45487.27	1.19E-10
19	34.92	0.03	219.41	48139.27	4.53E-10
20	37.45	0.03	235.28	55357.19	5.24E-09
21	39.98	0.03	251.23	63115.9	7.92E-08
22	41.23	0.02	259.05	67107.76	1.39E-07
23	41.99	0.02	263.82	69598.7	2.63E-07
24	43.78	0.02	275.11	75684.5	1.72E-06
25	45.32	0.02	284.76	81086.66	5.84E-06

* omega (ω) is in rad/s

In Table 4.1 the Eigen value (λ^{un}) is in the Eval column which equals ω^2. The low values in the Error column ensure that the computed results are reliable.



Vibration analysis
Code
Case : ST1
Mode : 1
f : 2,97 Hz
T : 0,337 s
ω : 18,66 rad/s
EVal : 348,03
Error : 1,39E-12
Iterations : 9
Comp. : eR

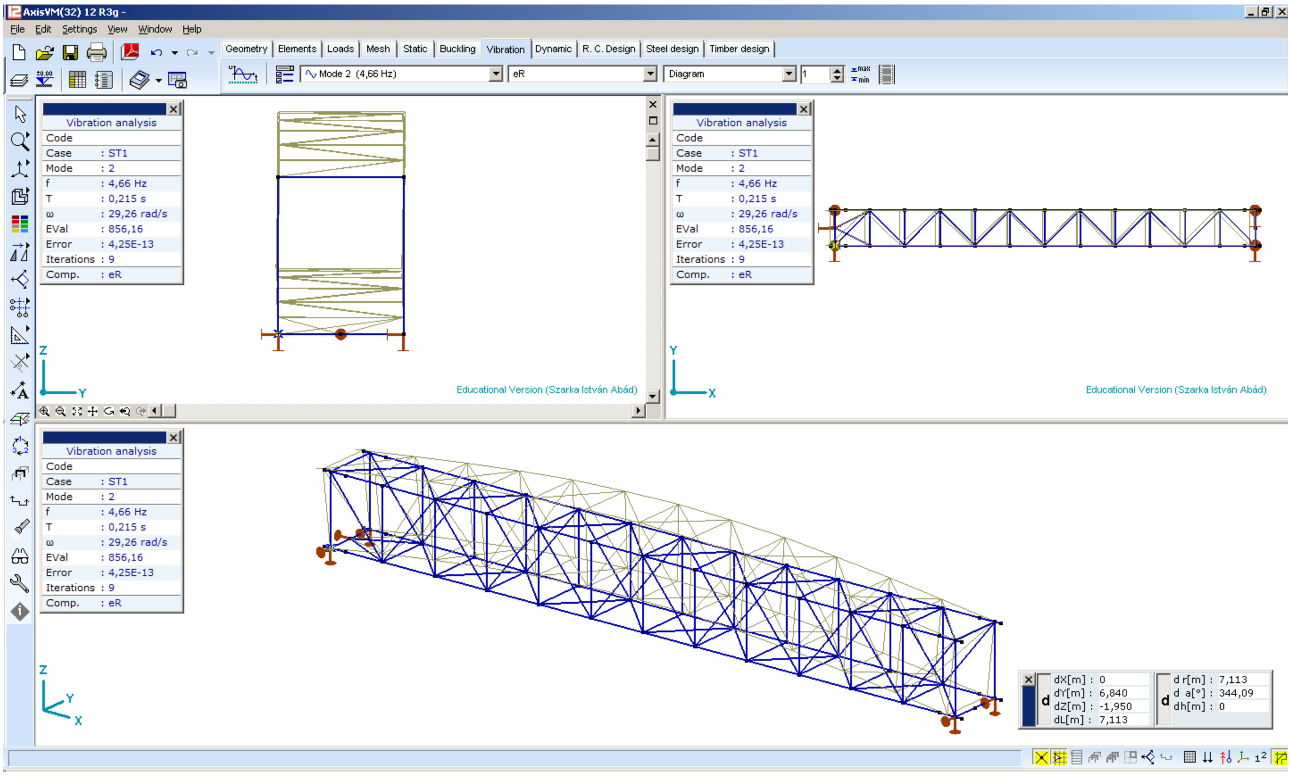
Vibration analysis
Code
Case : ST1
Mode : 1
f : 2,97 Hz
T : 0,337 s
ω : 18,66 rad/s
EVal : 348,03
Error : 1,39E-12
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 1
f : 2,97 Hz
T : 0,337 s
ω : 18,66 rad/s
EVal : 348,03
Error : 1,39E-12
Iterations : 9
Comp. : eR

dX[m] : -4,048
dY[m] : -17,646
dZ[m] : 0
dL[m] : 18,104

d r[m] : 18,104
d a[°] : 257,08
dh[m] : 0

Figure 4.1: Intact model - 1st mode shape - 2.97 Hz



Vibration analysis
Code
Case : ST1
Mode : 2
f : 4,66 Hz
T : 0,215 s
ω : 29,26 rad/s
EVal : 856,16
Error : 4,25E-13
Iterations : 9
Comp. : eR

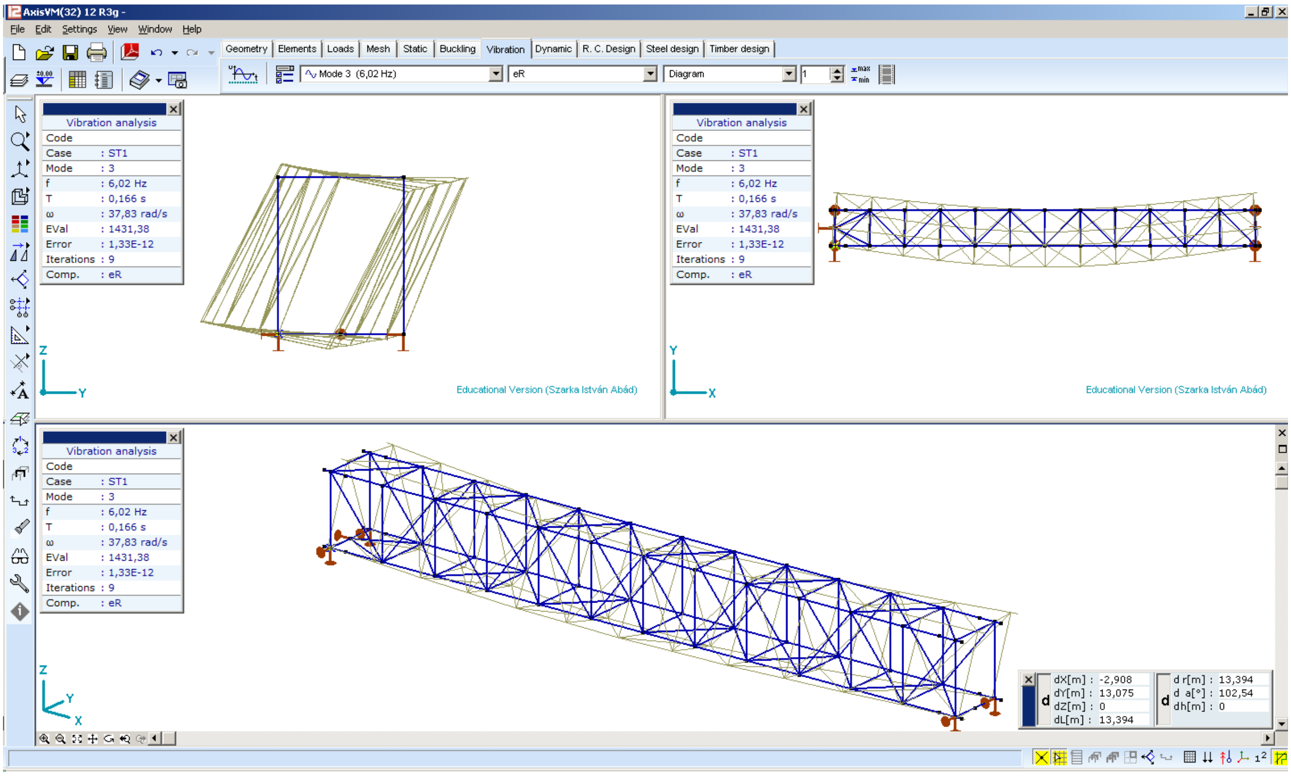
Vibration analysis
Code
Case : ST1
Mode : 2
f : 4,66 Hz
T : 0,215 s
ω : 29,26 rad/s
EVal : 856,16
Error : 4,25E-13
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 2
f : 4,66 Hz
T : 0,215 s
ω : 29,26 rad/s
EVal : 856,16
Error : 4,25E-13
Iterations : 9
Comp. : eR

dX[m] : 0
dY[m] : 6,840
dZ[m] : -1,950
dL[m] : 7,113

d r[m] : 7,113
d a[°] : 344,09
dh[m] : 0

Figure 4.2: Intact model - 2nd mode shape - 4.66 Hz



Vibration analysis
Code
Case : ST1
Mode : 3
f : 6,02 Hz
T : 0,166 s
ω : 37,83 rad/s
EVal : 1431,38
Error : 1,33E-12
Iterations : 9
Comp. : eR

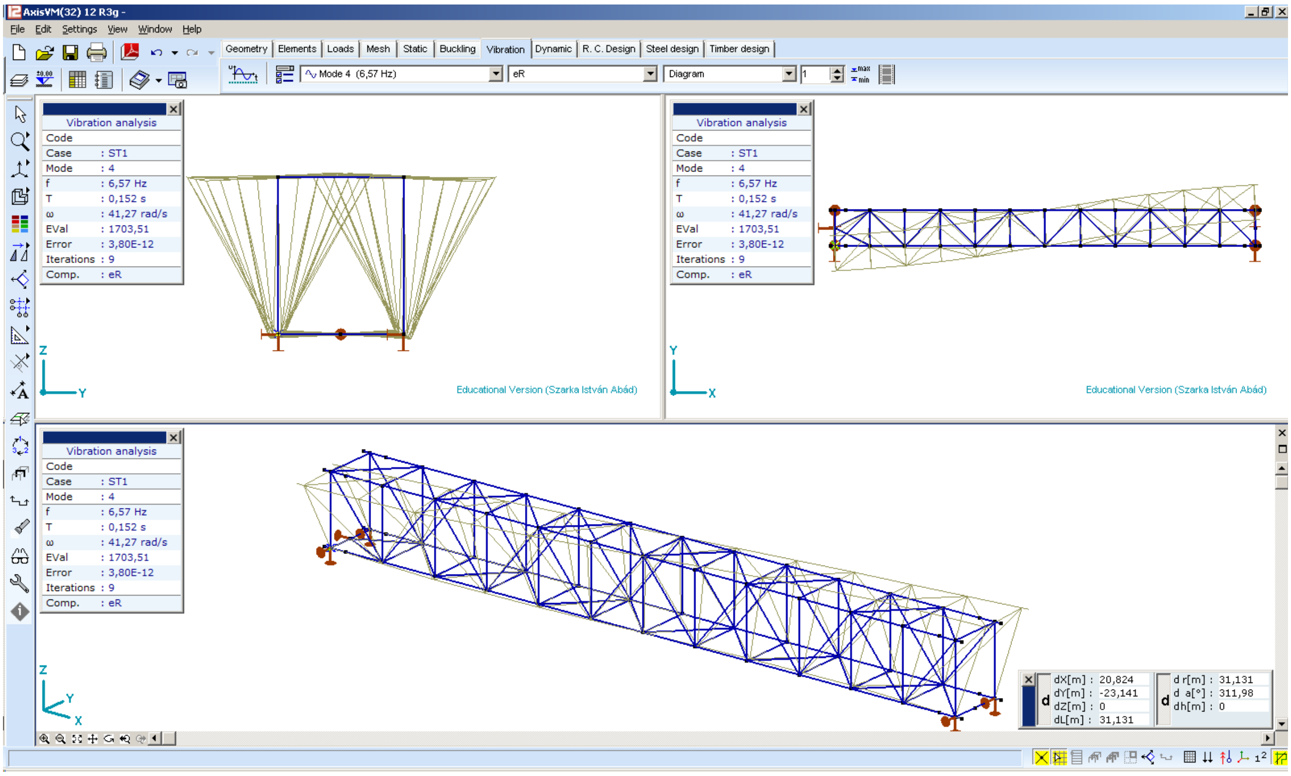
Vibration analysis
Code
Case : ST1
Mode : 3
f : 6,02 Hz
T : 0,166 s
ω : 37,83 rad/s
EVal : 1431,38
Error : 1,33E-12
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 3
f : 6,02 Hz
T : 0,166 s
ω : 37,83 rad/s
EVal : 1431,38
Error : 1,33E-12
Iterations : 9
Comp. : eR

dX[m] : -2,908
dY[m] : 13,075
dZ[m] : 0
dL[m] : 13,394

d r[m] : 13,394
d a[°] : 102,54
dh[m] : 0

Figure 4.3: Intact model - 3rd mode shape - 6.02 Hz



Vibration analysis
Code
Case : ST1
Mode : 4
f : 6,57 Hz
T : 0,152 s
ω : 41,27 rad/s
EVal : 1703,51
Error : 3,80E-12
Iterations : 9
Comp. : eR

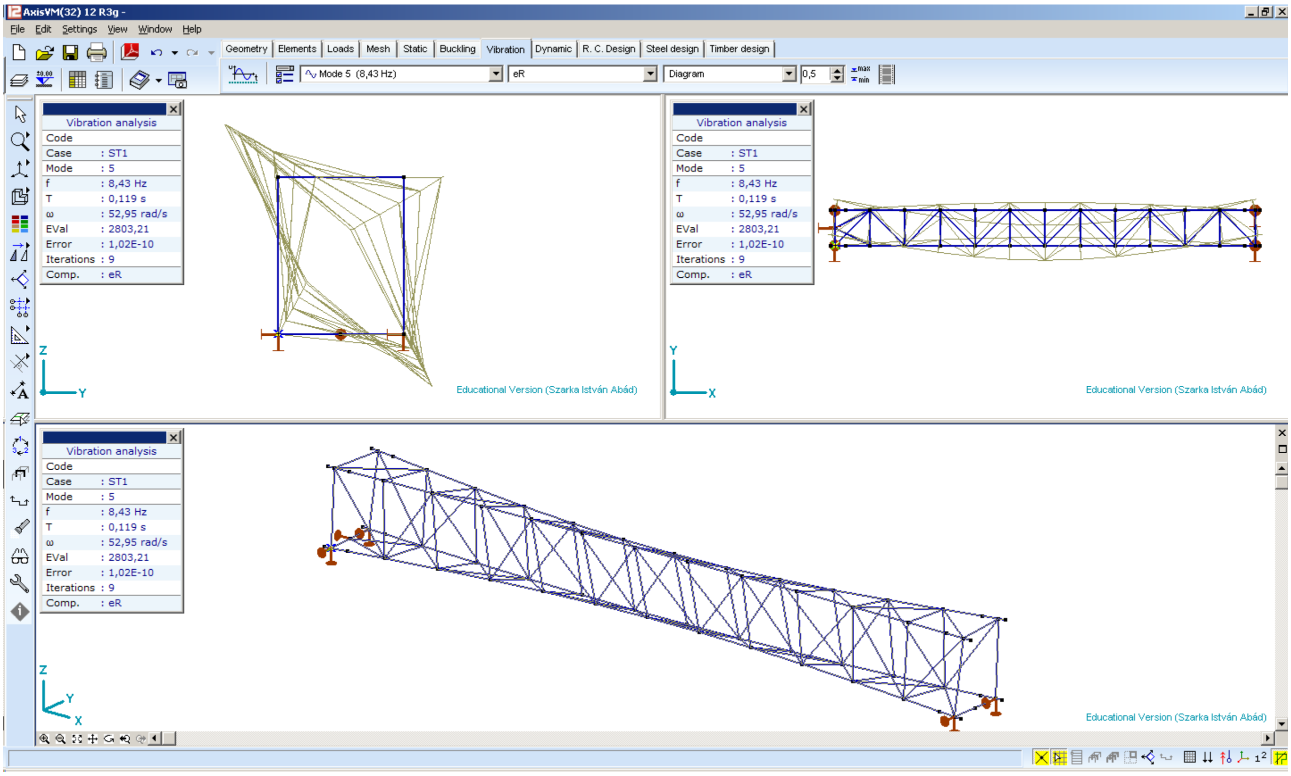
Vibration analysis
Code
Case : ST1
Mode : 4
f : 6,57 Hz
T : 0,152 s
ω : 41,27 rad/s
EVal : 1703,51
Error : 3,80E-12
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 4
f : 6,57 Hz
T : 0,152 s
ω : 41,27 rad/s
EVal : 1703,51
Error : 3,80E-12
Iterations : 9
Comp. : eR

dX[m] : 20,824
dY[m] : -23,141
dZ[m] : 0
dL[m] : 31,131

d r[m] : 31,131
d a[°] : 311,98
dh[m] : 0

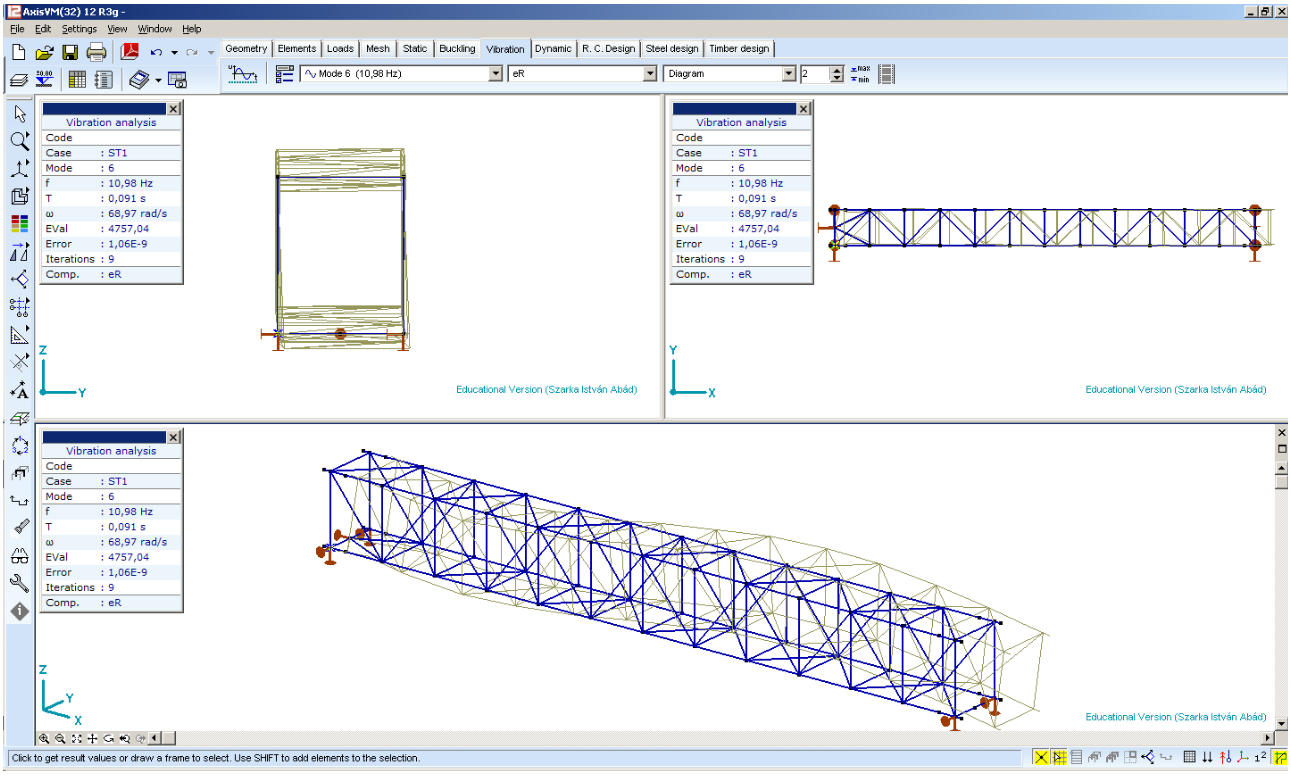
Figure 4.4: Intact model - 4th mode shape - 6.57 Hz



Mode 5 (8,43 Hz)
eR
Diagram
0,5

Vibration analysis
Code
Case : ST1
Mode : 5
f : 8,43 Hz
T : 0,119 s
ω : 52,95 rad/s
EVal : 2803,21
Error : 1,02E-10
Iterations : 9
Comp. : eR

Figure 4.5: Intact model - 5th mode shape - 8.43 Hz

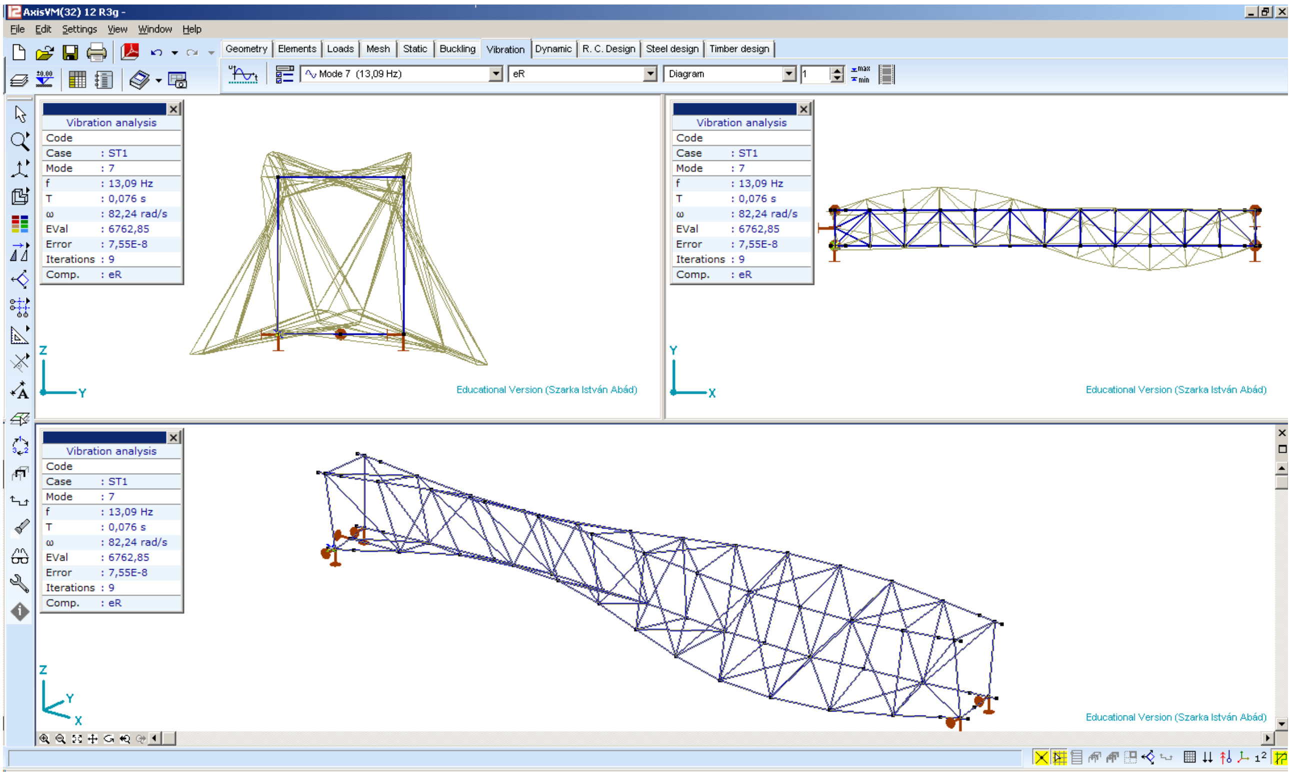


Mode 6 (10,98 Hz)
eR
Diagram
2

Vibration analysis
Code
Case : ST1
Mode : 6
f : 10,98 Hz
T : 0,091 s
ω : 68,97 rad/s
EVal : 4757,04
Error : 1,06E-9
Iterations : 9
Comp. : eR

Click to get result values or draw a frame to select. Use SHIFT to add elements to the selection.

Figure 4.6: Intact model - 6th mode shape - 10.98 Hz



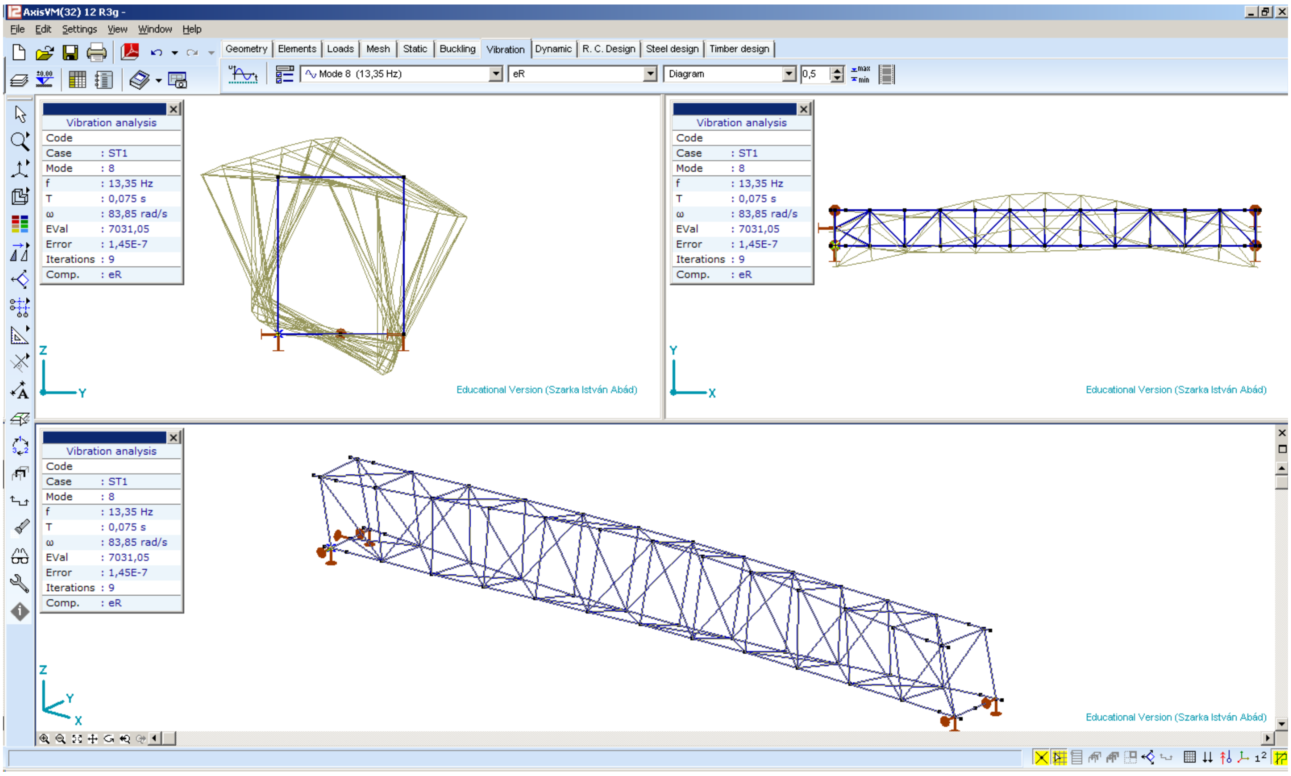
Mode 7 (13,09 Hz)
eR
Diagram
1

Vibration analysis
Code
Case : ST1
Mode : 7
f : 13,09 Hz
T : 0,076 s
ω : 82,24 rad/s
EVal : 6762,85
Error : 7,55E-8
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 7
f : 13,09 Hz
T : 0,076 s
ω : 82,24 rad/s
EVal : 6762,85
Error : 7,55E-8
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 7
f : 13,09 Hz
T : 0,076 s
ω : 82,24 rad/s
EVal : 6762,85
Error : 7,55E-8
Iterations : 9
Comp. : eR

Figure 4.7: Intact model - 7th mode shape - 13.09 Hz



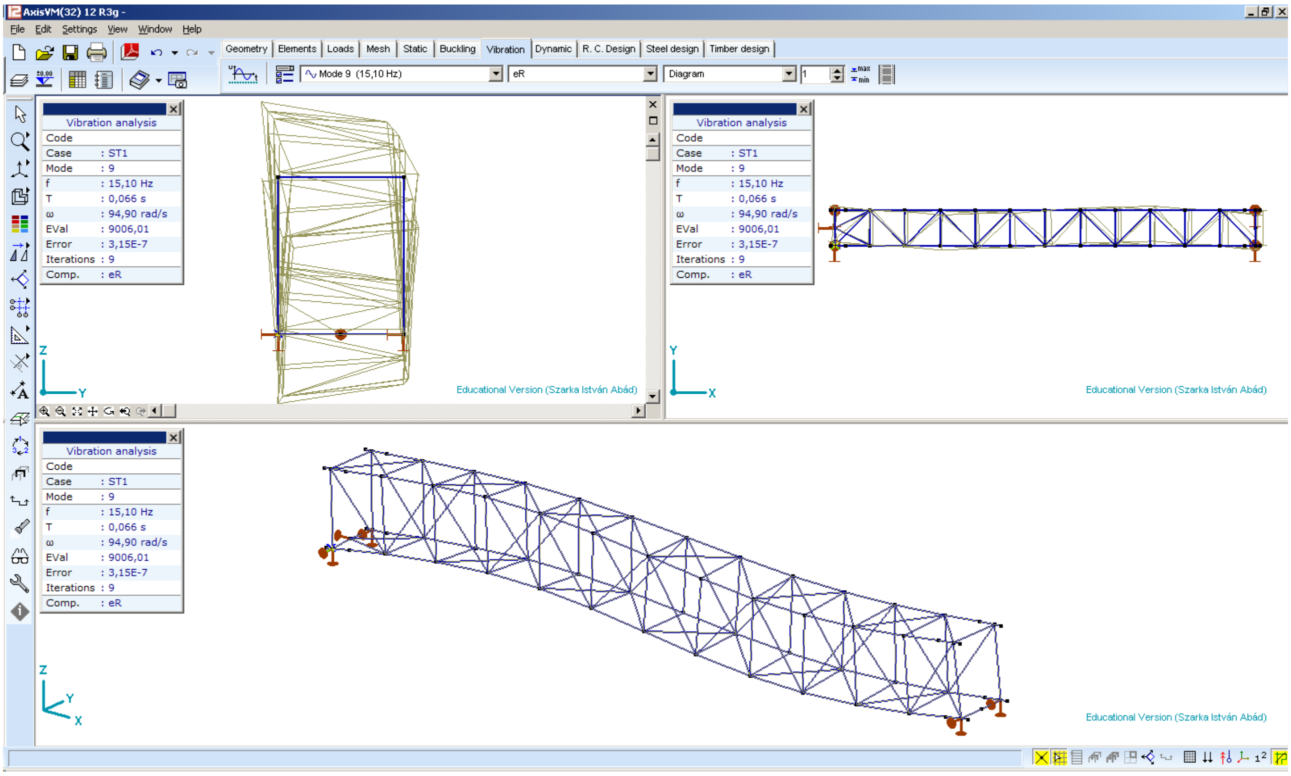
Mode 8 (13,35 Hz)
eR
Diagram
0,5

Vibration analysis
Code
Case : ST1
Mode : 8
f : 13,35 Hz
T : 0,075 s
ω : 83,85 rad/s
EVal : 7031,05
Error : 1,45E-7
Iterations : 9
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 8
f : 13,35 Hz
T : 0,075 s
ω : 83,85 rad/s
EVal : 7031,05
Error : 1,45E-7
Iterations : 9
Comp. : eR

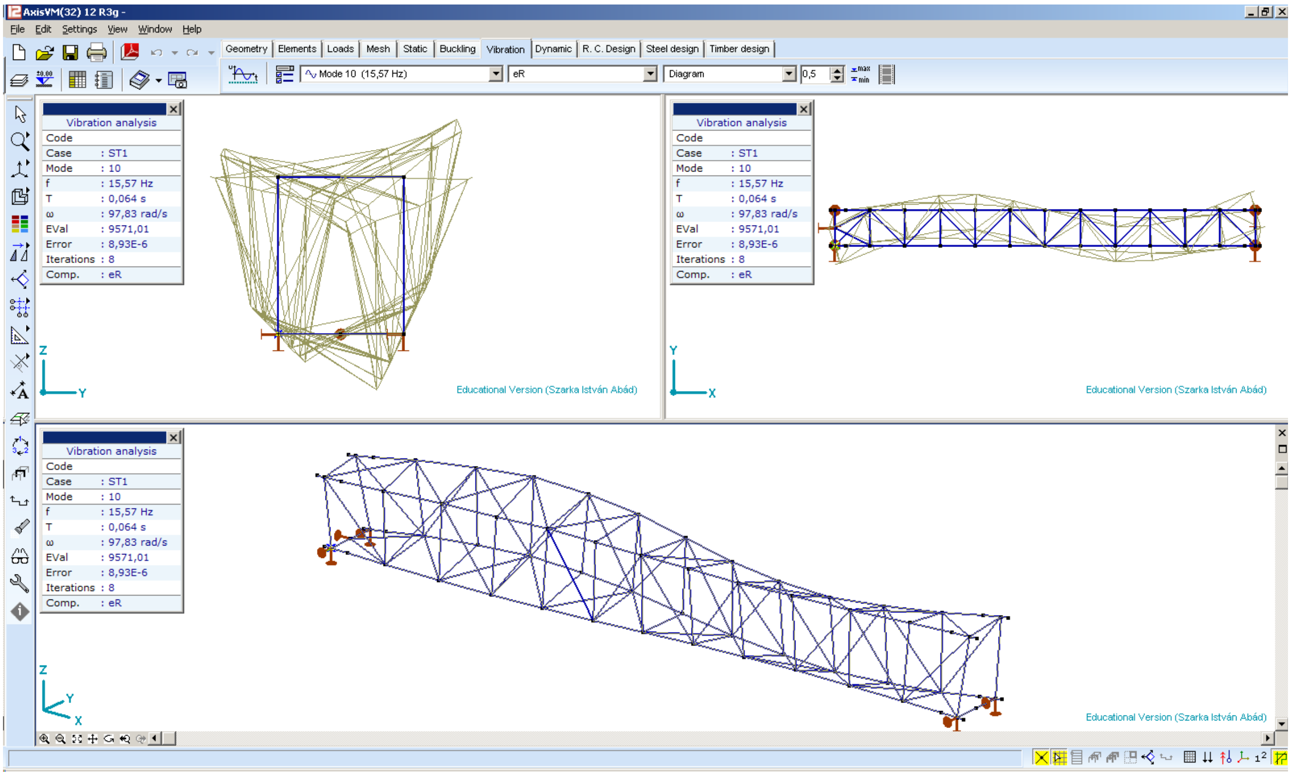
Vibration analysis
Code
Case : ST1
Mode : 8
f : 13,35 Hz
T : 0,075 s
ω : 83,85 rad/s
EVal : 7031,05
Error : 1,45E-7
Iterations : 9
Comp. : eR

Figure 4.8: Intact model - 8th mode shape - 13.35 Hz



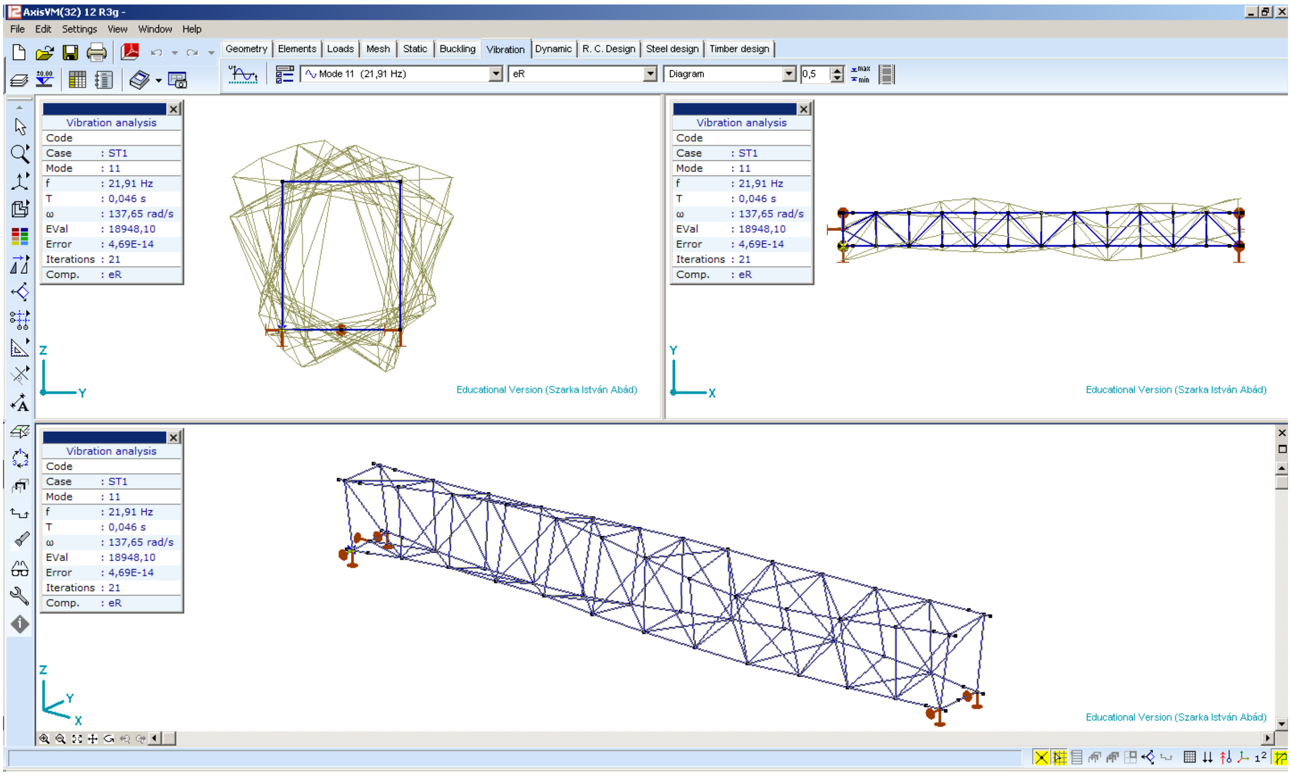
Vibration analysis
Code
Case : ST1
Mode : 9
f : 15,10 Hz
T : 0,066 s
ω : 94,90 rad/s
EVal : 9006,01
Error : 3,15E-7
Iterations : 9
Comp. : eR

Figure 4.9: Intact model - 9th mode shape - 15.10 Hz



Vibration analysis
Code
Case : ST1
Mode : 10
f : 15,57 Hz
T : 0,064 s
ω : 97,83 rad/s
EVal : 9571,01
Error : 8,93E-6
Iterations : 8
Comp. : eR

Figure 4.10: Intact model - 10th mode shape - 15.57 Hz



Vibration analysis
Code
Case : ST1
Mode : 11
f : 21,91 Hz
T : 0,046 s
ω : 137,65 rad/s
EVal : 18948,10
Error : 4,69E-14
Iterations : 21
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 11
f : 21,91 Hz
T : 0,046 s
ω : 137,65 rad/s
EVal : 18948,10
Error : 4,69E-14
Iterations : 21
Comp. : eR

Vibration analysis
Code
Case : ST1
Mode : 11
f : 21,91 Hz
T : 0,046 s
ω : 137,65 rad/s
EVal : 18948,10
Error : 4,69E-14
Iterations : 21
Comp. : eR

Figure 4.11: Intact model - 11th mode shape - 21.91 Hz

B5 Free vibration results and Consequence / Robustness factors for the damaged scenarios

In this chapter robustness is measured based on the methodology proposed by Olmati et al. /1/, but with the modification that, instead of using the Eigen values of the static stiffness matrix, it is the Eigen values of the free vibration problem that is used.

A set of damage scenarios are assumed where the damage is represented with a consequence factor ($C_f^{scenario}$ in Formula 5.1). The damage scenario is defined as the loss of one or several members (in this thesis only one member). Robustness is expressed as the complement of of $C_f^{scenario}$. (Formula 5.2)

$$C_f^{scenario} = max\left(\frac{\lambda_f^{un} - \lambda_f^{dam}}{\lambda_f^{un}} 100\right)_{f=1..N} \qquad \text{Formula 5.1}$$

$$R_{scenario} = 100 - C_f^{scenario} \qquad \text{Formula 5.2}$$

The consequence factor and the robustness is expressed in %. The higher percentage of C means higher consequences and less robustness in the given failure scenario.

In the above formulas λ_f^{un} and λ_f^{dam} are the Eigen value number *f* of the free vibration problem in the structure's intact and damaged condition.

B5.1 Summary of the results in section B8

In Table 5.1 a summary is provided of the results from section B8.

Table 5.1: Summary of results

Member	Consequence (C_f)	Critical Eigen mode
01 – Lower chord at support	40%	3
02 – Upper chord at support	33%	11
03 – Main diagonal (vertical) at support	26%	11
04 – Lower diagonal (horizontal) at support	33%	11
05 – Upper diagonal (horizontal) at support	34%	11
06 – Column above support	35%	11
07 – Lower chord at mid-span	49%	1

Initially it has to be noted about the results that many members have their most critical Eigen mode as no. 11, and the consequence is very often close to 30-35% with small variation.

Group of chord members: It is member 01, 02 and 07 that belong to this group. Member 01 and 07 have the highest consequence among all the investigated members in Table 5.1. From beam theory it is susceptible that member 07 should have a high consequence, but it is unlikely that member 01 has a consequence that is very close to member 07. It is even more unlikely that member 02 has a lower consequence than member 01. The reason for this is, if the elevation view is looked at and we imagine removing member 01, there is still a stiff, supported triangle transferring vertical forces to the top of the column. On the other hand if member 02 is removed the stiff triangle at the support becomes a bit "mechanism-like" in its connection to the main vertical girder of the bridge.

Diagonals: It is worth noting that in the results vertical diagonal have a lower consequence than the horizontals, as well as that there is not a significant difference between the lower and upper diagonal. This latter is unlikely because the loads will have to be transferred anyways to the supports at the lower points.

B5.1.1 Evaluation of the used method

Arguments in favor of the method (pros):

- Easy to perform the analysis
- Can be performed in the vast majority of structural FEM software
- Low on computational resources

Arguments against the method (cons):

- the results seem to contradict the gut feeling about the consequence of the members
- the results are not load specific: many structures are specifically designed for loads from a certain direction that is usually dimensioning (e.g. beam bridge for vertical loads)

B6 Modified methodology

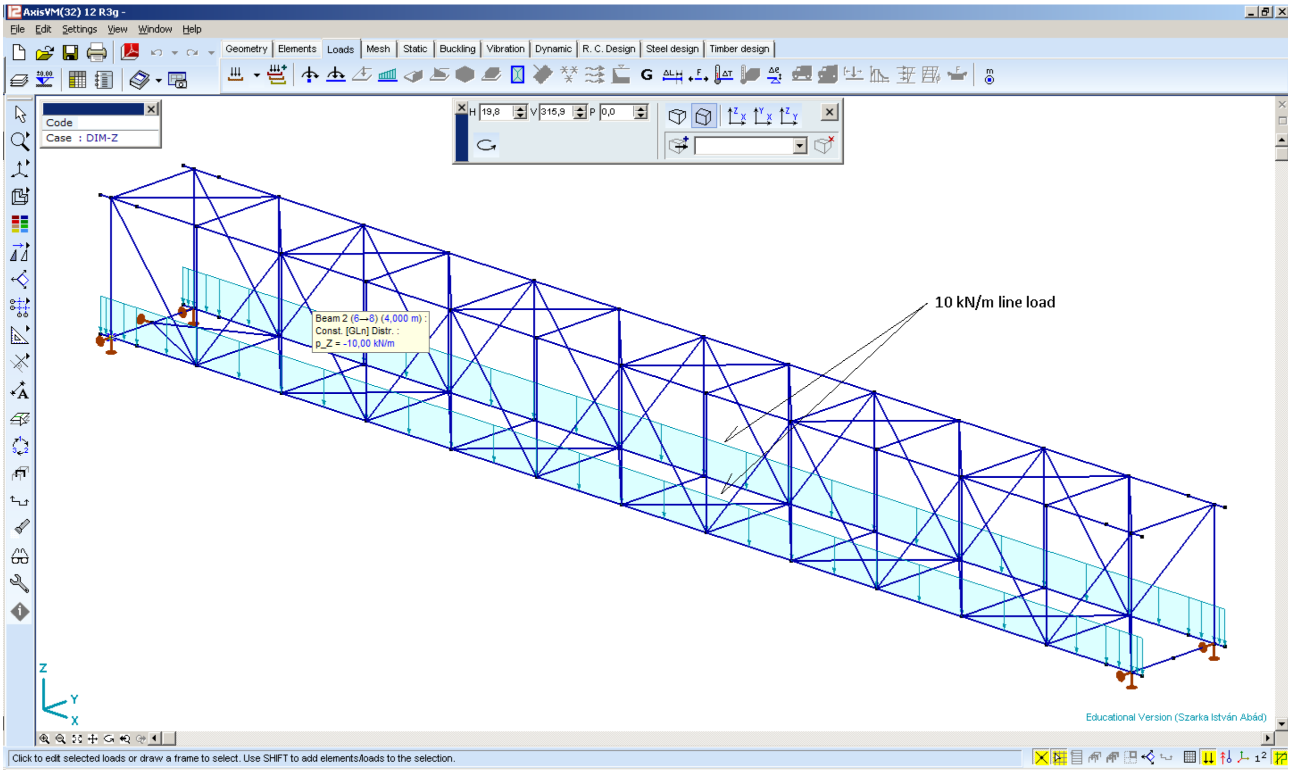
B6.1 Comparing the consequence values with code-check results

There seemed to be a need to compare the results with some other consequence measurements to see if the trends visible in section B5.1 can be verified or contradicted some way, which is more quantifiable than engineering gut feeling.

Ideally a push-over analysis would be performed to see the structure's behavior in a post-elastic condition. Due to software limitations, it has been decided to substitute this with using elastic code check results.

The following procedure has been followed:

- There has been a vertical load-case (DIM-Z) created that has a dummy load (10kN/m) along on the two lower chords (Figure 6.1)



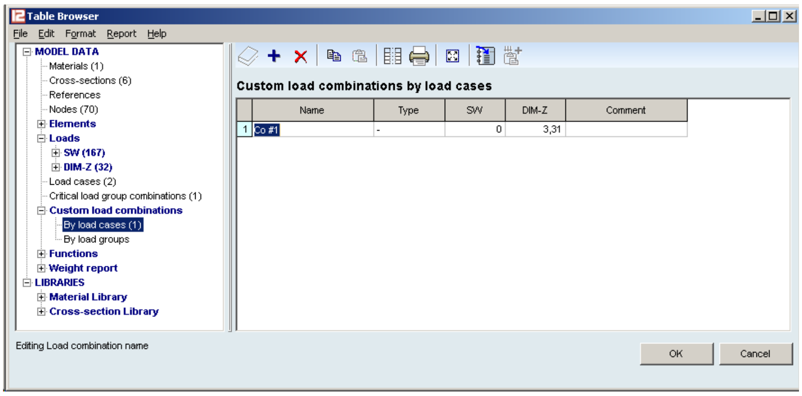
Code
Case : DIM-Z

Beam 2 (6→8) (4,000 m) :
Const. [GLn] Distr. :
p_Z = -10,00 kN/m

Click to edit selected loads or draw a frame to select. Use SHIFT to add elements/loads to the selection.

Figure 6.1: Vertical loadcase (DIM-Z)

- There has been a code-check load-combination created where the DIM-Z load-case is scale in such a way that the highest code-check result is 0.8 (Figure 6.2, Figure 6.3 and Figure 6.4). There was Eurocode /3/ used for code check with γ_{M0}=1.15. The other code-check parameters were set in a simple but conservative way.

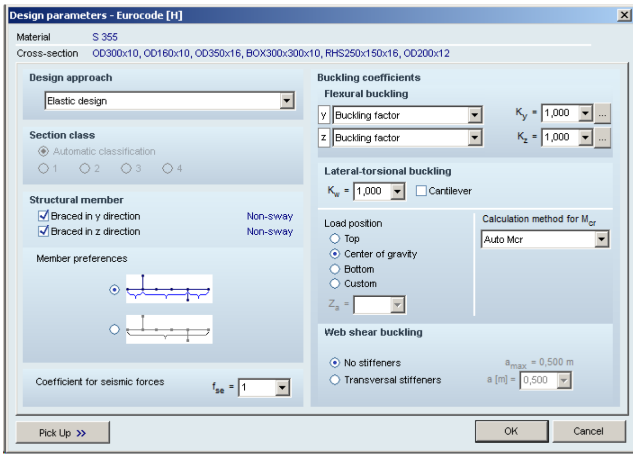


Custom load combinations by load cases

	Name	Type	SW	DIM-Z	Comment
1	Co #1	-	0	3,31	

Editing Load combination name

Figure 6.2: Scaling DIM-Z



Material S 355
Cross-section OD300x10, OD160x10, OD350x16, BOX300x300x10, RHS250x150x16, OD200x12
Design approach: Elastic design
Section class: ● Automatic classification ○ 1 ○ 2 ○ 3 ○ 4
☑ Braced in y direction Non-sway
☑ Braced in z direction Non-sway
Coefficient for seismic forces f_{se} = 1
y Buckling factor K_y = 1,000
z Buckling factor K_z = 1,000
K_w = 1,000 ☐ Cantilever
Load position: ○ Top ● Center of gravity ○ Bottom ○ Custom Z_a =
Calculation method for M_{cr}: Auto Mcr
● No stiffeners ○ Transversal stiffeners a_{max} = 0,500 m a [m] = 0,500

Figure 6.3: Code check parameters (Eurocode)

- Afterwards the selected members were removed one-by-one from the structure and the code-check was re-run. The summary of results is shown in Table 6.1

Table 6.1: Summary of code-check results

Intact Model	Removed member													
	01		02		03		04		05		06		07	
UF_{max}	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ	UF_{max}	Δ
0.80	0.80	0.05	1.69	1.60	1.44	1.25	0.80	0.05	0.80	0.01	1.56	1.40	2.16	1.39

The results in Table 6.1 are all maximum values. For each model with one removed member the maximum utilization factor and the maximum UF change (Δ) is shown. The change in the UF value gives a hint about how critical it was to remove a member, while Δ can show, to some extent, how much the internal forces were rearranged due to the member removal.

It is visible by the first look that member 01, 04 and 05 made very little change in the utilizations.

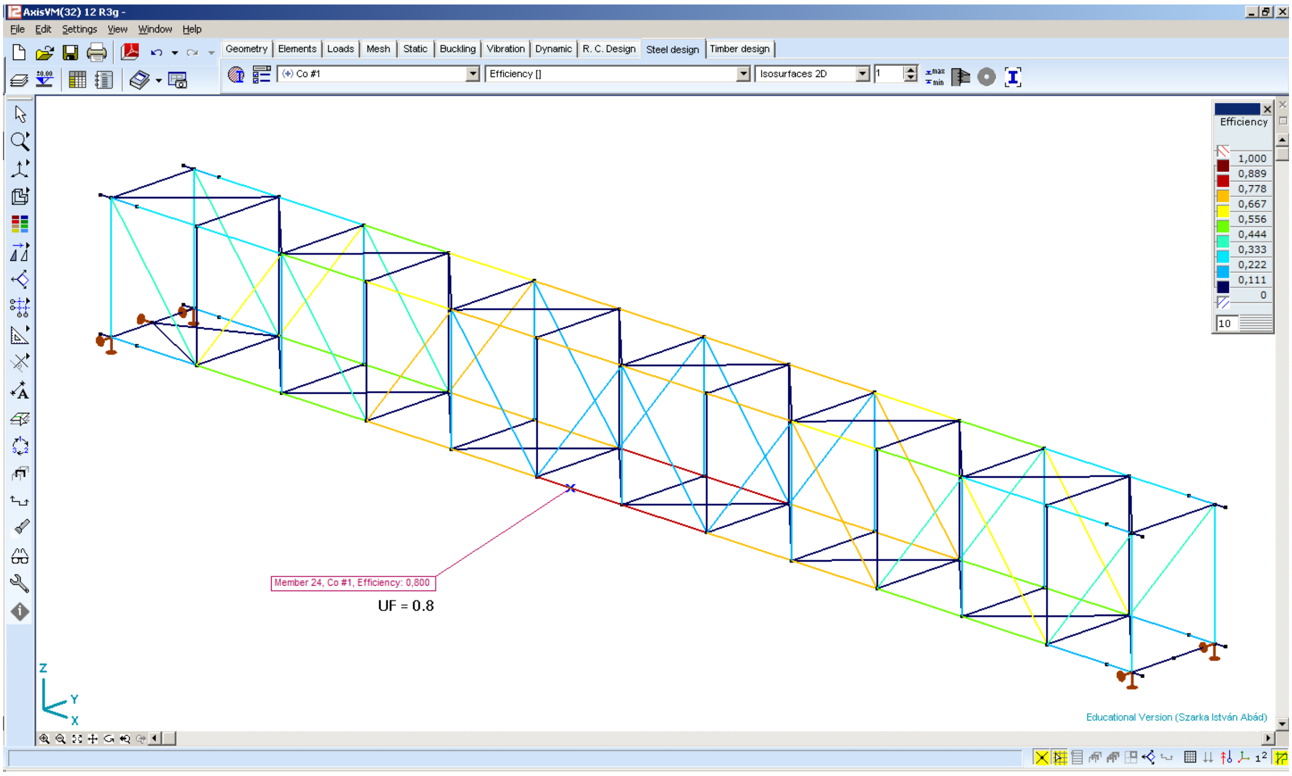


Figure 6.4: Utilization tuned to 0.8 in the chord at midspan

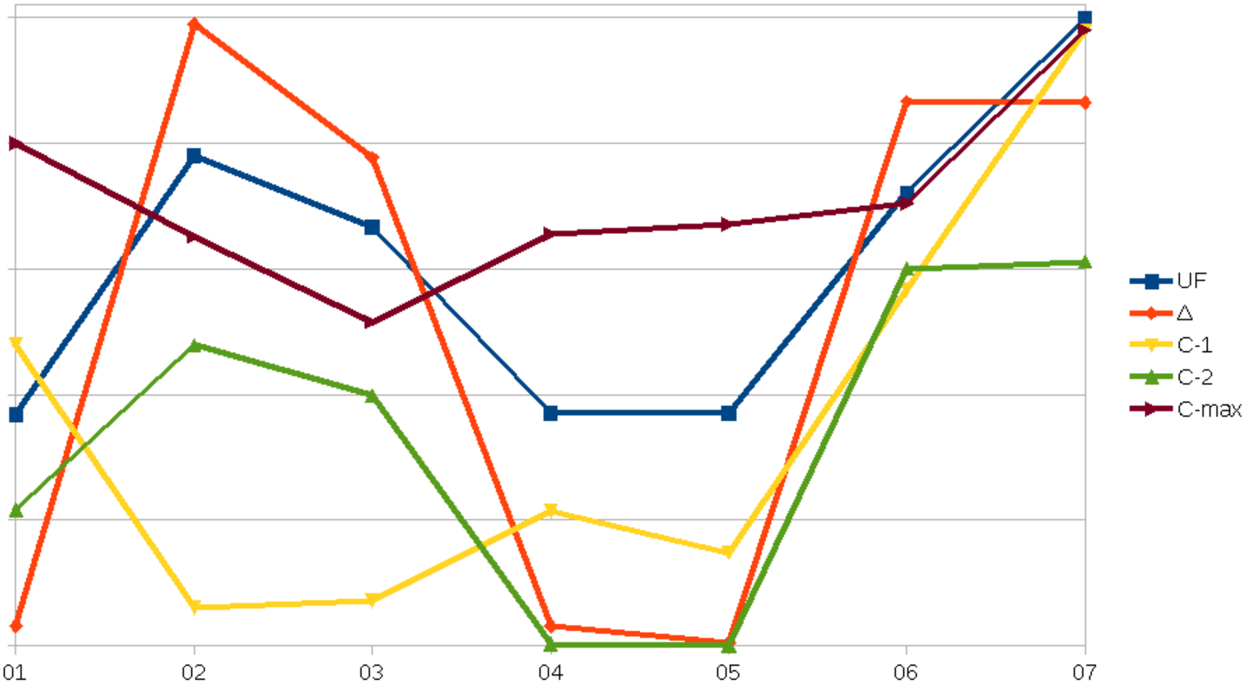


Figure 6.5: Result summary

In Figure 6.5:

- UF is the utilization factor from Table 6.1, the values are scaled
- Δ from Table 6.1, the values are scaled
- C-1 is the consequence according to Formula 5.1, with the modification that is is not the maximum difference chosen from all the Eigen values, but it is the difference in Eigen value no.1. The first Eigen mode is a horizontal bending mode (Figure 4.1).
- C-2, similar to C-1, but it is Eigen mode no.2 from (Figure 4.2) which the Eigen values are taken. This mode is a vertical bending and the *shape resembles very much to the expected deformation plot from gravity* or vertical live loads (negative).
- C-max is the consequence according to Formula 5.1, the results are from Table 5.1

B6.2 Evaluation of the modified methodology

It can be seen in the section above that the real modification compared to Formula 5.1 is that instead of taking maximum difference from all the investigated Eigen values, it is one particular taken. I.e. instead of looking at all the modes, one or some of them is selected on the basis of having similarity between the mode shape and the expected deformation plot from the given load.

The Figure 6.5 was created to highlight the *positive correlation between UF and C-2, and also between Δ and C-2*. The correlation between UF and C-2 is true for all members but 07, and the correlation between Δ and C-2 seems to be present for all members.

It is worth looking at the line of C-1 which belongs to the first horizontal bending mode. There seems to be a negative correlation with UF at member 04 and 05, but the results match the gut-feeling of member 04 having higher consequence (lower brace) than 05.

Compared to the original methodology, it is an improvement that there seems to be a way to become more load specific, or directional.

B7 Possible further improvements

In spite of the the visible correlation in the modified methodology, there should be done many tests / analyses to be able to verify and prove its reliability, furthermore:

1) Consequence values should be compared to push-over analysis results
2) It should be investigated how results are affected with structures that include high concentrated masses.
3) It should be looked at how the involved mass in each Eigen mode is in connection with the results – e.g. consequence value more or less relevant if participating mass is high or low, totally or in a given direction

4) Find out if the Cmax values cannot be used or if they imply a behavior that can reveal non-load specific properties of the structure.

B8 Tables of results of the vibration analyses

B8.1 Member 01 – Lower chord at support

Table 8.1: Results of the free vibration analysis – Damaged model – Member 01 removed

No	f [Hz]	T [s]	omega	EVal (λ^{dam})	EVal (λ^{un})	Error	$C_f^{scenario}$
1	2.59	0.39	16.26	264.53	348.03	2.02E-12	*24%*
2	4.4	0.23	27.63	763.58	856.16	2.01E-12	*11%*
3	**4.66**	**0.21**	**29.3**	**858.76**	**1431.38**	**4.41E-13**	***40%***
4	6.34	0.16	39.81	1585.15	1703.51	5.68E-13	*7%*
5	8.42	0.12	52.88	2796.72	2803.21	1.71E-13	*0%*
6	8.81	0.11	55.36	3065.1	4757.04	3.04E-13	*36%*
7	11.05	0.09	69.42	4819.08	6762.85	1.92E-13	*29%*
8	13.27	0.08	83.41	6956.6	7031.05	1.57E-13	*1%*
9	15.09	0.07	94.82	8991.75	9006.01	4.22E-14	*0%*
10	15.21	0.07	95.56	9132.67	9571.01	5.36E-14	*5%*
11	17.06	0.06	107.16	11483.99	18948.11	1.28E-13	*39%*
12	22.05	0.05	138.55	19195.02	19452.21	4.26E-14	*1%*
13	24.24	0.04	152.3	23194.43	23803.57	3.47E-14	*3%*
14	24.8	0.04	155.85	24288.89	24825.58	1.58E-14	*2%*
15	26.47	0.04	166.32	27662.31	35734.13	2.77E-14	*23%*
16	30.47	0.03	191.47	36661.89	39184.9	4.92E-13	*6%*
17	33.23	0.03	208.81	43601.14	43635.05	3.13E-11	*0%*
18	33.37	0.03	209.7	43972.1	45487.27	1.81E-11	*3%*
19	34.91	0.03	219.32	48102.35	48139.27	2.68E-10	*0%*
20	35.79	0.03	224.89	50573.96	55357.19	1.62E-10	*9%*
21	38.1	0.03	239.37	57299.5	63115.9	7.12E-09	*9%*
22	41.27	0.02	259.32	67246.97	67107.76	1.31E-07	*0%*
23	41.91	0.02	263.32	69336.85	69598.7	1.05E-07	*0%*
24	42.88	0.02	269.4	72576.15	75684.5	3.23E-07	*4%*
25	44.44	0.02	279.23	77970.74	81086.66	5.64E-06	*4%*
						max Cf:	***40%***

From Table 8.1 it is visible that $C_f^{Member01}$= 40% and the removal of Member 01 has the greatest effect on Eigen mode no. 3.

B8.2 Member 02 – Upper chord at support

Table 8.2: Results of the free vibration analysis – Damaged model – Member 02 removed

No	f [Hz]	T [s]	omega	EVal	EVal	Error	Cf
1	2.92	0.34	18.37	337.48	348.03	1.78E-12	*3%*
2	4.06	0.25	25.52	651.33	856.16	7.87E-13	*24%*
3	5.72	0.18	35.95	1292.26	1431.38	9.22E-13	*10%*
4	6.54	0.15	41.1	1689.33	1703.51	4.96E-13	*1%*
5	8.01	0.13	50.3	2529.87	2803.21	5.13E-13	*10%*
6	9.08	0.11	57.07	3257.01	4757.04	4.89E-13	*32%*
7	11.6	0.09	72.86	5309.03	6762.85	1.90E-13	*21%*
8	13.09	0.08	82.25	6764.89	7031.05	5.58E-14	*4%*
9	13.61	0.07	85.53	7314.53	9006.01	1.21E-13	*19%*
10	15.43	0.07	96.92	9394.06	9571.01	6.59E-14	*2%*
11	**17.99**	**0.06**	**113.03**	**12775.38**	**18948.11**	**9.68E-14**	***33%***
12	22.01	0.05	138.3	19126.83	19452.21	5.22E-14	*2%*
13	22.3	0.05	140.09	19626.33	23803.57	2.58E-14	*18%*
14	25.12	0.04	157.81	24903.5	24825.58	1.07E-13	*0%*
15	27.95	0.04	175.64	30848.51	35734.13	8.08E-12	*14%*
16	30.17	0.03	189.55	35929.47	39184.9	4.78E-11	*8%*
17	31.58	0.03	198.43	39375.62	43635.05	3.78E-10	*10%*
18	33.86	0.03	212.76	45266.5	45487.27	1.98E-09	*0%*
19	34.64	0.03	217.64	47368.6	48139.27	1.02E-08	*2%*
20	37.43	0.03	235.19	55316.68	55357.19	8.44E-08	*0%*
21	37.78	0.03	237.39	56353.27	63115.9	2.26E-07	*11%*
22	39.99	0.03	251.28	63142.11	67107.76	3.90E-07	*6%*
23	42.04	0.02	264.13	69762.94	69598.7	2.22E-06	*0%*
24	43.8	0.02	275.18	75722.14	75684.5	5.25E-06	*0%*
25	44.99	0.02	282.65	79892.61	81086.66	5.51E-06	*1%*
						max Cf:	***33%***

It can be seen in Table 8.2 that $C_f^{Member02}$= 33% and the removal of Member 02 has the greatest effect on Eigen mode no. 11.

B8.3 Member 03 – Main diagonal (vertical) at support

Table 8.3: Results of the free vibration analysis – Damaged model – Member 03 removed

No	**f [Hz]**	**T [s]**	**omega**	**EVal**	**EVal**	**Error**	**Cf**
1	2.92	0.34	18.32	335.52	348.03	2.25E-12	*4%*
2	4.17	0.24	26.19	685.73	856.16	4.65E-13	*20%*
3	5.73	0.17	36.02	1297.47	1431.38	5.04E-13	*9%*
4	6.57	0.15	41.25	1701.53	1703.51	8.56E-13	*0%*
5	8.32	0.12	52.26	2730.79	2803.21	1.25E-13	*3%*
6	10.06	0.1	63.22	3997.16	4757.04	2.15E-13	*16%*
7	11.42	0.09	71.75	5148.6	6762.85	2.33E-13	*24%*
8	13.11	0.08	82.4	6789.46	7031.05	4.38E-14	*3%*
9	14.28	0.07	89.72	8050.57	9006.01	5.32E-14	*11%*
10	15.64	0.06	98.25	9652.25	9571.01	7.52E-14	*1%*
11	**18.88**	**0.05**	**118.6**	**14065.02**	**18948.11**	**6.87E-14**	***26%***
12	22.23	0.05	139.7	19517.17	19452.21	1.98E-14	*0%*
13	23.5	0.04	147.67	21806.57	23803.57	1.83E-14	*8%*
14	25.05	0.04	157.38	24769.66	24825.58	2.74E-14	*0%*
15	28.1	0.04	176.53	31161.57	35734.13	1.86E-14	*13%*
16	31.57	0.03	198.33	39334.39	39184.9	4.50E-14	*0%*
17	32.29	0.03	202.91	41173.59	43635.05	1.21E-13	*6%*
18	33.99	0.03	213.57	45613.81	45487.27	7.01E-13	*0%*
19	34.86	0.03	219.05	47981.35	48139.27	1.38E-11	*0%*
20	36.47	0.03	229.14	52505.97	55357.19	1.89E-11	*5%*
21	40.21	0.03	252.65	63829.86	63115.9	7.82E-09	*1%*
22	40.48	0.03	254.36	64698.07	67107.76	6.26E-09	*4%*
23	41.79	0.02	262.6	68957.01	69598.7	1.03E-08	*1%*
24	43.58	0.02	273.81	74970.03	75684.5	1.07E-07	*1%*
25	45.68	0.02	287.01	82372.39	81086.66	2.85E-06	*2%*
						max Cf:	***26%***

It can be seen in Table 8.3 that $C_f^{Member02}$= 26% and the removal of Member 03 has the greatest effect on Eigen mode no. 11.

B8.4 Member 04 – Lower diagonal (horizontal) at support

Table 8.4: Results of the free vibration analysis – Damaged model – Member 04 removed

No	f [Hz]	T [s]	omega	EVal	EVal	Error	Cf
1	2.81	0.36	17.63	310.72	348.03	1.66E-12	*11%*
2	4.66	0.22	29.28	857.16	856.16	7.88E-13	*0%*
3	5.12	0.2	32.18	1035.87	1431.38	1.94E-12	*28%*
4	6.37	0.16	40	1599.92	1703.51	6.44E-13	*6%*
5	8.43	0.12	52.94	2802.35	2803.21	2.87E-13	*0%*
6	9.93	0.1	62.42	3896.1	4757.04	3.25E-13	*18%*
7	11.01	0.09	69.16	4783.77	6762.85	2.90E-13	*29%*
8	13.28	0.08	83.43	6959.94	7031.05	1.17E-13	*1%*
9	15.12	0.07	94.99	9023.82	9006.01	6.62E-14	*0%*
10	15.34	0.07	96.38	9289.18	9571.01	1.10E-13	*3%*
11	**17.97**	**0.06**	**112.89**	**12744.4**	**18948.11**	**8.84E-14**	***33%***
12	22.08	0.05	138.71	19241.5	19452.21	4.39E-14	*1%*
13	24.35	0.04	153	23408.84	23803.57	4.21E-14	*2%*
14	24.91	0.04	156.5	24493.12	24825.58	1.95E-14	*1%*
15	27.28	0.04	171.41	29380.46	35734.13	1.52E-13	*18%*
16	30.61	0.03	192.3	36979.46	39184.9	1.40E-11	*6%*
17	33.2	0.03	208.58	43505.25	43635.05	2.58E-10	*0%*
18	33.8	0.03	212.36	45095.14	45487.27	2.02E-10	*1%*
19	35	0.03	219.9	48354.98	48139.27	2.17E-09	*0%*
20	35.93	0.03	225.78	50977.12	55357.19	1.51E-09	*8%*
21	38.37	0.03	241.09	58124.53	63115.9	2.12E-08	*8%*
22	41.23	0.02	259.03	67094.17	67107.76	3.54E-07	*0%*
23	42.03	0.02	264.07	69731.95	69598.7	1.24E-06	*0%*
24	43.16	0.02	271.15	73523.59	75684.5	8.31E-07	*3%*
25	44.64	0.02	280.49	78677.18	81086.66	5.99E-06	*3%*
						max Cf:	*33%*

It can be seen in Table 8.4 that $C_f^{Member02}$= 33% and the removal of Member 04 has the greatest effect on Eigen mode no. 11.

B8.5 Member 05 – Upper diagonal (horizontal) at support

Table 8.5: Results of the free vibration analysis – Damaged model – Member 05 removed

No	f [Hz]	T [s]	omega	EVal	EVal	Error	Cf
1	2.86	0.35	17.95	322.3	348.03	1.98E-12	*7%*
2	4.66	0.22	29.26	856.39	856.16	4.02E-13	*0%*
3	6.02	0.17	37.83	1431.43	1431.38	5.72E-13	*0%*
4	6.61	0.15	41.51	1723.49	1703.51	4.33E-13	*1%*
5	8.43	0.12	52.96	2805.1	2803.21	1.98E-13	*0%*
6	11.02	0.09	69.25	4794.97	4757.04	2.23E-13	*1%*
7	11.75	0.09	73.84	5453.05	6762.85	1.66E-13	*19%*
8	13.09	0.08	82.24	6763.99	7031.05	5.48E-14	*4%*
9	14.43	0.07	90.67	8221.15	9006.01	8.06E-14	*9%*
10	15.14	0.07	95.12	9048.33	9571.01	3.49E-14	*5%*
11	**17.86**	**0.06**	**112.24**	**12597.76**	**18948.11**	**4.21E-14**	***34%***
12	22.2	0.05	139.51	19463.74	19452.21	2.56E-14	*0%*
13	23.05	0.04	144.84	20979.72	23803.57	2.10E-13	*12%*
14	24.88	0.04	156.36	24447.14	24825.58	4.25E-14	*2%*
15	27.23	0.04	171.1	29275.8	35734.13	2.41E-13	*18%*
16	31.5	0.03	197.93	39178.09	39184.9	2.50E-12	*0%*
17	31.68	0.03	199.03	39613.94	43635.05	7.89E-12	*9%*
18	33.64	0.03	211.39	44685	45487.27	1.32E-10	*2%*
19	35.02	0.03	220.06	48426.3	48139.27	2.59E-10	*1%*
20	36.02	0.03	226.33	51226.65	55357.19	1.45E-09	*7%*
21	39.61	0.03	248.86	61930.48	63115.9	1.99E-08	*2%*
22	40.01	0.03	251.38	63190.15	67107.76	1.09E-07	*6%*
23	41.81	0.02	262.72	69021.1	69598.7	1.37E-07	*1%*
24	43.64	0.02	274.17	75168.61	75684.5	1.60E-06	*1%*
25	45.31	0.02	284.72	81065.23	81086.66	4.15E-06	*0%*
						max Cf:	***34%***

It can be seen in Table 8.5 that $C_f^{Member02}$= 34% and the removal of Member 05 has the greatest effect on Eigen mode no. 11.

B8.6 Member 06 – Column above support

Table 8.6: Results of the free vibration analysis – Damaged model – Member 06 removed

No	f [Hz]	T [s]	omega	EVal	EVal	Error	Cf
1	2.51	0.4	15.8	249.59	348.03	3.35E-12	*28%*
2	3.9	0.26	24.48	599.39	856.16	9.99E-13	*30%*
3	5.42	0.18	34.08	1161.34	1431.38	7.84E-13	*19%*
4	6.13	0.16	38.51	1483.38	1703.51	1.04E-12	*13%*
5	8.07	0.12	50.74	2574.17	2803.21	1.28E-13	*8%*
6	9.14	0.11	57.41	3295.34	4757.04	3.49E-13	*31%*
7	11.26	0.09	70.77	5009.03	6762.85	1.94E-13	*26%*
8	13.09	0.08	82.23	6761.97	7031.05	5.01E-14	*4%*
9	13.98	0.07	87.86	7719.73	9006.01	9.68E-14	*14%*
10	15.57	0.06	97.82	9568.67	9571.01	7.51E-14	*0%*
11	**17.64**	**0.06**	**110.82**	**12281.32**	**18948.11**	**8.84E-14**	***35%***
12	22.14	0.05	139.1	19347.73	19452.21	1.85E-14	*1%*
13	23.09	0.04	145.05	21039.49	23803.57	3.50E-14	*12%*
14	25.02	0.04	157.22	24716.88	24825.58	3.88E-14	*0%*
15	26.99	0.04	169.61	28766.06	35734.13	2.77E-14	*19%*
16	31.19	0.03	195.99	38411.9	39184.9	1.69E-12	*2%*
17	31.79	0.03	199.75	39899.45	43635.05	2.11E-12	*9%*
18	33.94	0.03	213.27	45485.52	45487.27	1.29E-11	*0%*
19	34.71	0.03	218.1	47568	48139.27	2.01E-10	*1%*
20	35.8	0.03	224.93	50593.7	55357.19	2.42E-10	*9%*
21	39.02	0.03	245.18	60115.64	63115.9	7.01E-09	*5%*
22	40.03	0.03	251.5	63249.83	67107.76	5.32E-08	*6%*
23	41.72	0.02	262.15	68722.67	69598.7	1.74E-07	*1%*
24	43.04	0.02	270.41	73120.38	75684.5	3.56E-07	*3%*
25	44.79	0.02	281.41	79189.1	81086.66	3.20E-06	*2%*
						max Cf:	***35%***

It can be seen in Table 8.6 that $C_f^{Member02}$= 35% and the removal of Member 06 has the greatest effect on Eigen mode no. 11.

B8.7 Member 07 – Lower chord at mid-span

Table 8.7: Results of the free vibration analysis – Damaged model – Member 07 removed

No	f [Hz]	T [s]	omega	EVal	EVal	Error	Cf
1	**2.12**	**0.47**	**13.33**	**177.61**	**348.03**	**5.15E-12**	***49%***
2	3.88	0.26	24.38	594.52	856.16	1.24E-12	*31%*
3	5.83	0.17	36.63	1342.12	1431.38	7.16E-13	*6%*
4	6.56	0.15	41.23	1699.92	1703.51	6.41E-13	*0%*
5	8.4	0.12	52.79	2786.43	2803.21	2.03E-13	*1%*
6	10.78	0.09	67.74	4588.67	4757.04	2.19E-13	*4%*
7	12.61	0.08	79.24	6278.89	6762.85	1.10E-13	*7%*
8	13.34	0.08	83.83	7028.26	7031.05	1.47E-13	*0%*
9	15.04	0.07	94.49	8928.28	9006.01	6.24E-14	*1%*
10	15.36	0.07	96.53	9317.33	9571.01	9.51E-14	*3%*
11	19.73	0.05	123.97	15369.39	18948.11	4.69E-14	*19%*
12	21.94	0.05	137.83	18995.94	19452.21	3.53E-14	*2%*
13	23.89	0.04	150.11	22532.58	23803.57	1.88E-14	*5%*
14	24.89	0.04	156.38	24454.66	24825.58	2.69E-14	*1%*
15	29.61	0.03	186.03	34607.78	35734.13	2.34E-13	*3%*
16	30.42	0.03	191.15	36539.97	39184.9	6.17E-13	*7%*
17	32.87	0.03	206.53	42652.71	43635.05	6.11E-12	*2%*
18	33.86	0.03	212.73	45254.42	45487.27	6.26E-12	*1%*
19	34.1	0.03	214.27	45913.31	48139.27	1.51E-10	*5%*
20	37.36	0.03	234.74	55103.91	55357.19	1.97E-09	*0%*
21	39.64	0.03	249.09	62046.6	63115.9	1.09E-08	*2%*
22	40.97	0.02	257.42	66263.26	67107.76	7.02E-08	*1%*
23	41.73	0.02	262.2	68748.89	69598.7	5.98E-07	*1%*
24	43.74	0.02	274.84	75537.17	75684.5	1.04E-06	*0%*
25	44.84	0.02	281.72	79368.97	81086.66	6.56E-06	*2%*
						max Cf:	***49%***

It can be seen in Table 8.7 that $C_f^{Member02}$= 49% and the removal of Member 07 has the greatest effect on Eigen mode no. 1.

B9 References

/1/ Olmati P, Gkoumas K, Brando F, Cao L. Consequence-based robustness assessment of a steel truss bridge. Steel Compos Struct 2013;14:379–95.
/2/ InterCad Kft. AxisVM Overview n.d. http://axisvm.eu/axisvm_products_overview.html (accessed May 15, 2015).
/3/ European Comitee for Standardization. Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings. EN 1993-1-1:2005. 2005.

Appendix C

DNV GL' SIMS program
Screenshots and functions

Table of Contents

List of Figures

C1 Introduction

DNV GL's SIMS software (Structural Integrity Management System) is suited to assist the operation of fixed offshore structural assets with particular focus on structural integrity, change and inspection management. The goal of the software is to maintain and give access to the database, with special structural engineering aspects, that contains data on facilities, their yearly inspections, findings and the follow-ups of analyses. Archiving is an important feature of the program.

It has to be emphasized that the used SIMS version in this thesis is a test version, hence the database does not contain data that match reality, even though platform names may match those of real platforms.

In Figure 1.1 the typical SIMS screen is shown, which has 5 distinguished areas. The Task bar which lists the different portals, and the sub functions within each portal.

The “Listing of main data” area usually contains a list of items that belong to the category selected in the Task bar. It is usually possible to perform searches here or filter the list based on aggregated KPI statuses.

Below this there is the “detailed information tabs” where detailed information can be seen of the selected item from the list above.

The “3D viewer” part can show the structural configuration of the selected structure. It can display the structure with proportional dimensions and correct cross sections. It purpose is to visually help locating inspections, findings or to display statuses with color-coding. The structural members and joints are identified with names which the 3D viewer can also display.

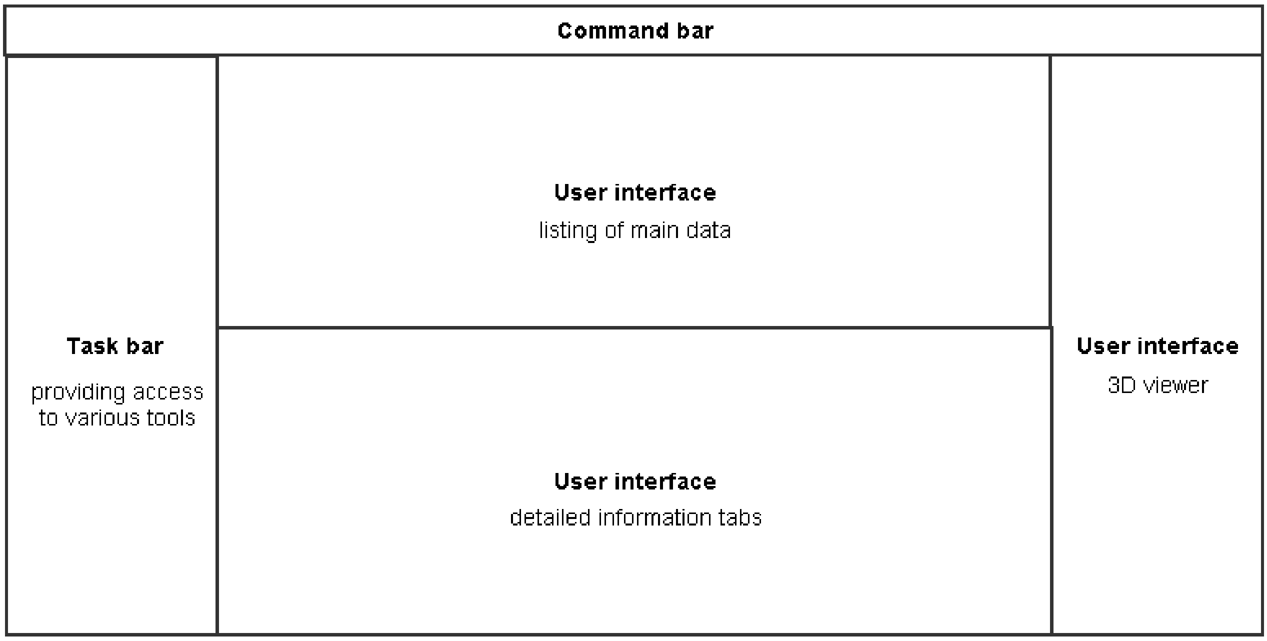


Figure 1.1: SIMS screen arrangement

The main sources used for this appendix is the SIMS manual /1/ and own use and experience with SIMS.

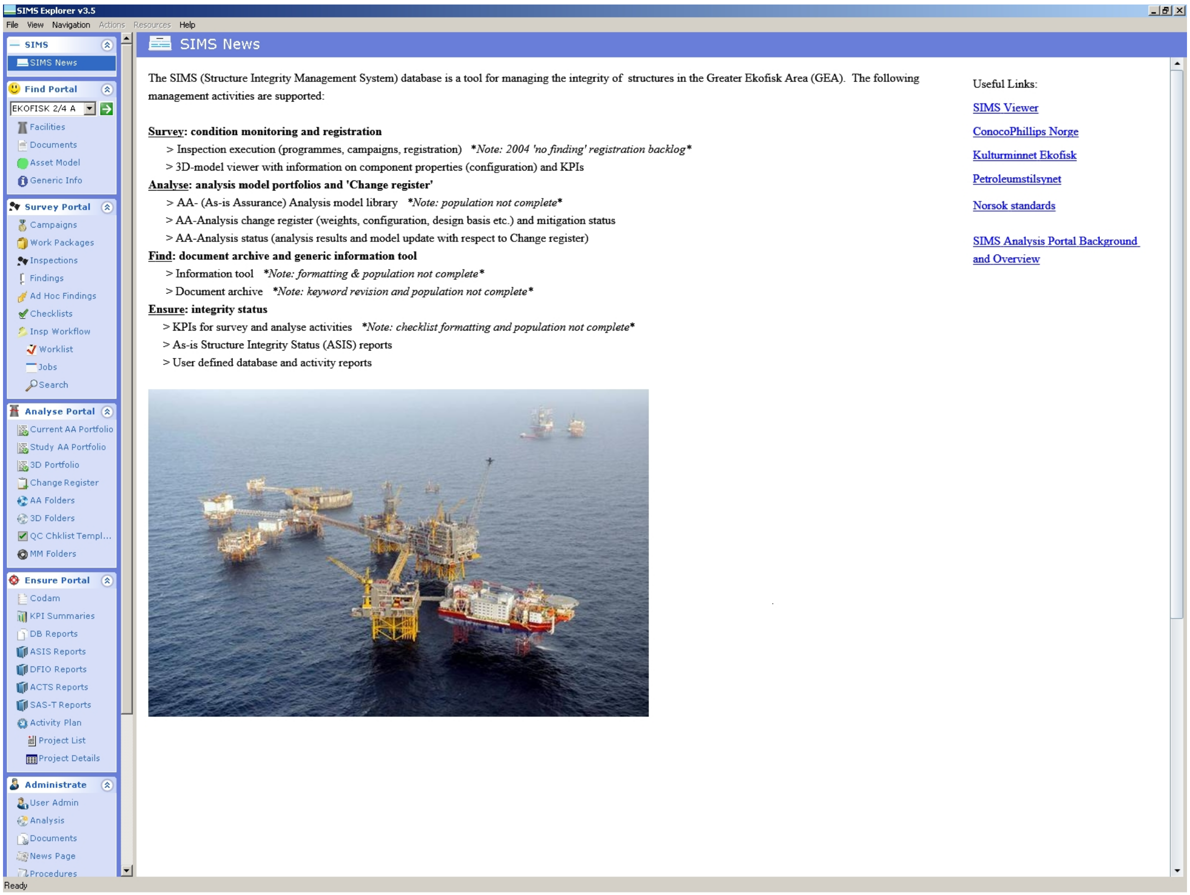
C2 Program modules

The program consists of several modules that allow insight to asset integrity statuses on levels that vary from details of asset properties to high level (managerial) overviews through the use of KPI propagation. The main sections of the program are (as they are displayed from the bottom to the top) SIMS News, Find Portal (SIMS-f), Survey Portal (SIMS-s), Analysis Portal (SIMS-a), Ensure Portal (SIMS-e) and the Administrate Portal.

The structure of this appendix in the following is that each portal (one-by-one) is introduced with figures and there is a description of some of the most important available functions.

C2.1 SIMS News

In Figure 2.1 the SIMS News window is shown. This is a customizable screen to broadcast messages to the users of SIMS. It can display texts, pictures or hyperlinks. The customization can be done by a user with administrative privileges in the Administrative Portal.



The SIMS (Structure Integrity Management System) database is a tool for managing the integrity of structures in the Greater Ekofisk Area (GEA). The following management activities are supported:

<u>Survey</u>: condition monitoring and registration
> Inspection execution (programmes, campaigns, registration) **Note: 2004 'no finding' registration backlog**
> 3D-model viewer with information on component properties (configuration) and KPIs
<u>Analyse</u>: analysis model portfolios and 'Change register'
> AA- (As-is Assurance) Analysis model library **Note: population not complete**
> AA-Analysis change register (weights, configuration, design basis etc.) and mitigation status
> AA-Analysis status (analysis results and model update with respect to Change register)
<u>Find</u>: document archive and generic information tool
> Information tool **Note: formatting & population not complete**
> Document archive **Note: keyword revision and population not complete**
<u>Ensure</u>: integrity status
> KPIs for survey and analyse activities **Note: checklist formatting and population not complete**
> As-is Structure Integrity Status (ASIS) reports
> User defined database and activity reports

Useful Links:

SIMS Viewer

ConocoPhillips Norge

Kulturminnet Ekofisk

Petroleumstilsynet

Norsok standards

SIMS Analysis Portal Background and Overview

Figure 2.1: SIMS News

C2.2 Find portal

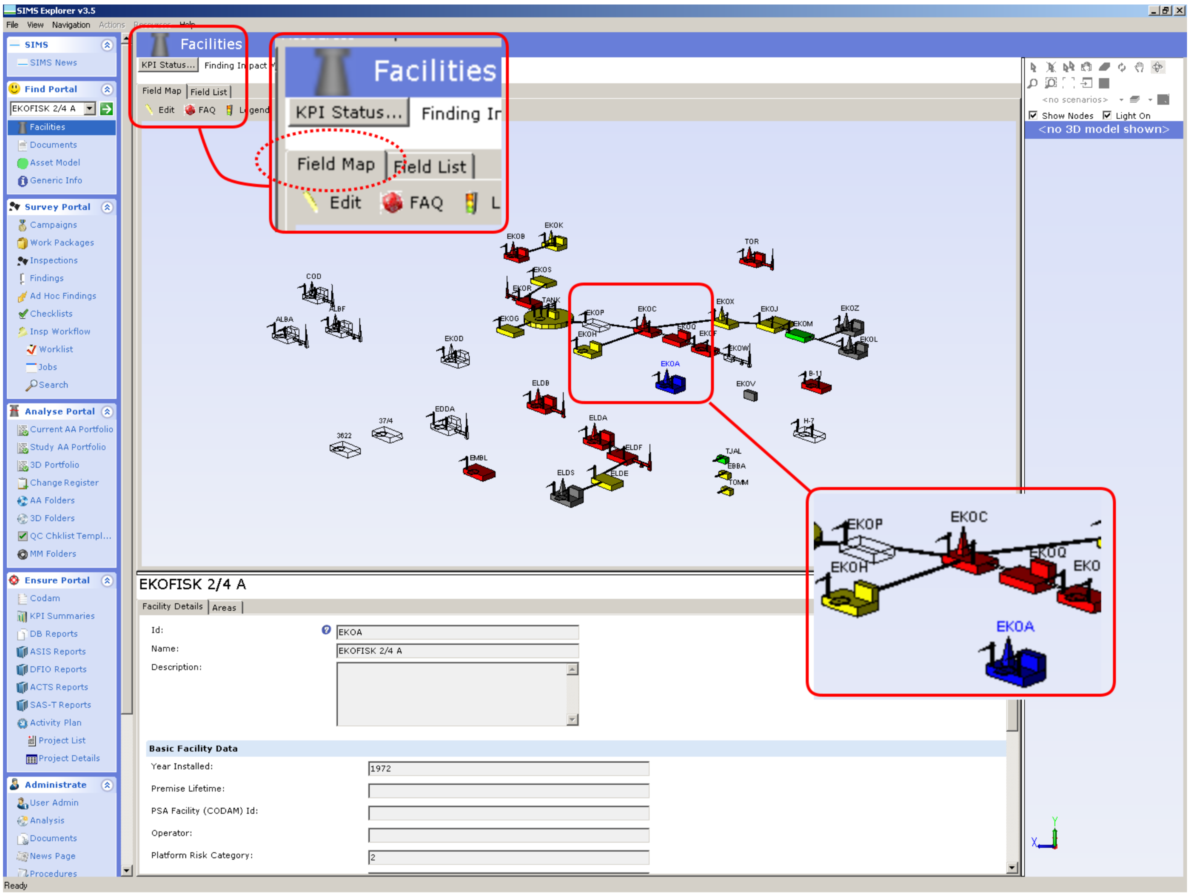
The find portal is shown in Figure 2.2 with the *Field map tab* activated. This portal is used to select a particular platform to be able to work with in the subsequent portals. The selected facility is highlighted with blue color in the *Facilities tool* if the *Field map tab* is active. In the Field map the other platforms are shown with different colors. It is the *Legend* button that gives information on the actual meaning of colors, based on KPI propagation. From the Field map tab one can change to the *Field list tab* (Figure 2.3), which gives a more detail oriented overview of the facilities included in SIMS. Under the Field list basic information are available about the structure (e.g. installation year, operator). It is also possible to see the Major Structure Areas of the facility. With the *KPI status button* (Figure 2.4) a pop-up window can be opened that makes it possible to choose a status selector, this way filtering the list of facilities. The available options are:

- No KPI
- Finding Impact Mitigation Status (if the findings of the surveys have been mitigated)
- Inspection Schedule Status (being worked on; Assigned; Completed; Cancelled; needs Review)
- Work Package Schedule Status (planned, completed or being worked on)
- Campaign Schedule Status (completed or being worked on)
- Operational status (disused, operating, removed, not set)
- Configuration Status (fill, cathodic protection, marine growth, anode consumption, exterior situation, clamp status)

The *Documents tool* in the Task bar enables access to all documents (any file) stored in the database. A particular document is stored only once in the SIMS database, but can be linked to many locations. As many other objects in SIMS, documents are stored together with a series of attributes, tags (meta-data) that include fields which are particular for the given document (e.g. title, author, type, project, revision, etc.)

The *Asset model tool* in the Task bar shows the break down structure of the SIMS asset, i.e. what major parts are distinguished for the structure in SIMS. The following areas can be defined for a structure: A (Topside), B (Bridge), C (MSS – Module Support Structure), F (Flare), G (GBS – gravity based structure), H (Helideck), J (Jacket Main), K (Crane Pedestal), T (Jacket Bridge), W (Seabed Template/Wells), M (Module), X (Foundation). The area can partly be seen in Figure 2.5 together with the structural view of the asset in the 3D viewer window. It can also be seen in this picture that each area can have a series of typical data that are listed in the “detailed information tabs” area together with linked documents, inspections and findings.

The *Generic Info tool* in the Task bar provides quick access to key information and documents considered to be of high importance by the company. A user with administrative rights can set up the format of this page in the Administration portal. Data stored here can be viewed and edited also. Beyond data a figure can also be attached to the Generic Info



EKOFISK 2/4 A

Facility Details | Areas

Id: EKOA

Name: EKOFISK 2/4 A

Description:

Basic Facility Data

Year Installed: 1972

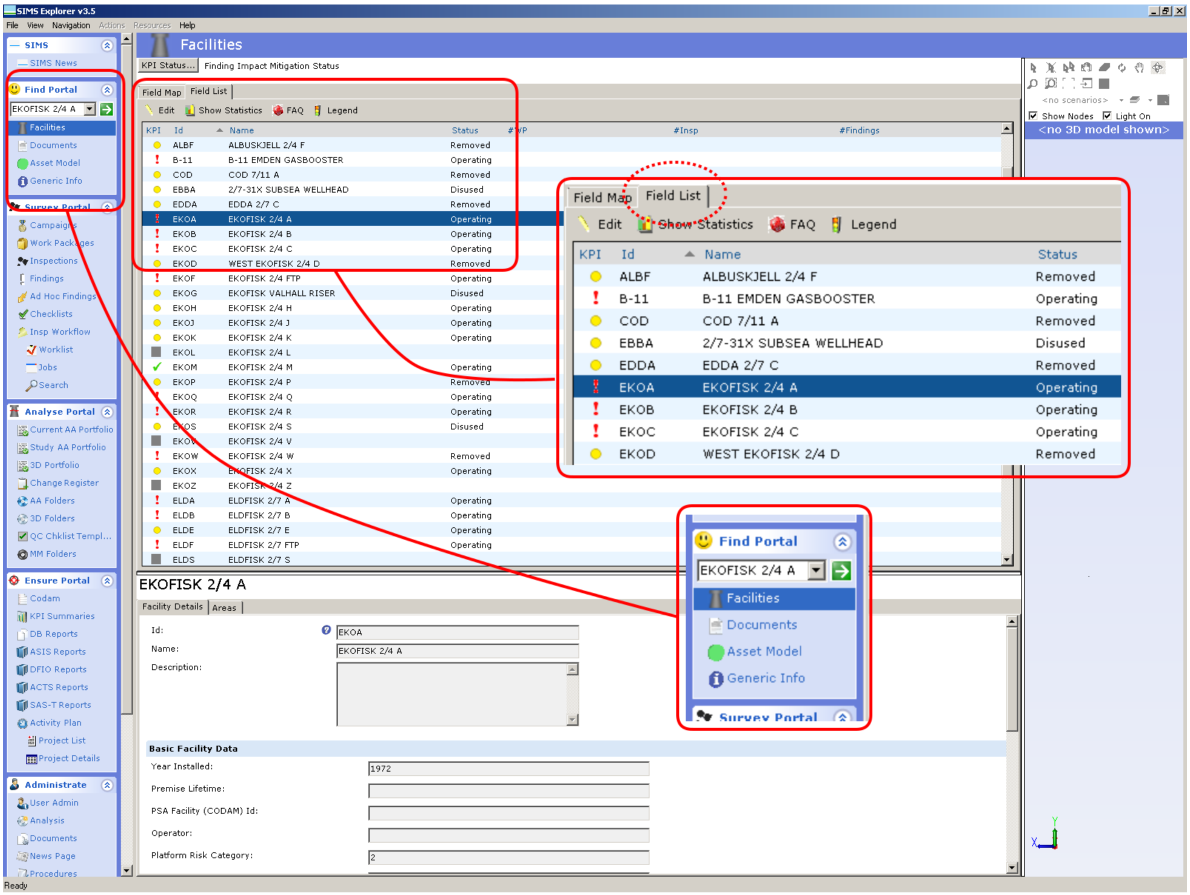
Premise Lifetime:

PSA Facility (CODAM) Id:

Operator:

Platform Risk Category: 2

Figure 2.2: Find portal – Field map tab



KPI	Id	Name	Status	#WP	#Insp	#Findings
●	ALBF	ALBUSKJELL 2/4 F	Removed			
!	B-11	B-11 EMDEN GASBOOSTER	Operating			
●	COD	COD 7/11 A	Removed			
●	EBBA	2/7-31X SUBSEA WELLHEAD	Disused			
●	EDDA	EDDA 2/7 C	Removed			
!	EKOA	EKOFISK 2/4 A	Operating			
!	EKOB	EKOFISK 2/4 B	Operating			
!	EKOC	EKOFISK 2/4 C	Operating			
●	EKOD	WEST EKOFISK 2/4 D	Removed			
!	EKOF	EKOFISK 2/4 FTP	Operating			
●	EKOG	EKOFISK VALHALL RISER	Disused			
●	EKOH	EKOFISK 2/4 H	Operating			
●	EKOJ	EKOFISK 2/4 J	Operating			
●	EKOK	EKOFISK 2/4 K	Operating			
■	EKOL	EKOFISK 2/4 L				
✓	EKOM	EKOFISK 2/4 M	Operating			
●	EKOP	EKOFISK 2/4 P	Removed			
!	EKOQ	EKOFISK 2/4 Q	Operating			
!	EKOR	EKOFISK 2/4 R	Operating			
●	EKOS	EKOFISK 2/4 S	Disused			
■	EKOV	EKOFISK 2/4 V				
!	EKOW	EKOFISK 2/4 W	Removed			
●	EKOX	EKOFISK 2/4 X	Operating			
■	EKOZ	EKOFISK 2/4 Z				
!	ELDA	ELDFISK 2/7 A	Operating			
!	ELDB	ELDFISK 2/7 B	Operating			
●	ELDE	ELDFISK 2/7 E	Operating			
!	ELDF	ELDFISK 2/7 FTP	Operating			
■	ELDS	ELDFISK 2/7 S				

EKOFISK 2/4 A

Facility Details | Areas

Id: EKOA

Name: EKOFISK 2/4 A

Description:

Basic Facility Data

Year Installed: 1972

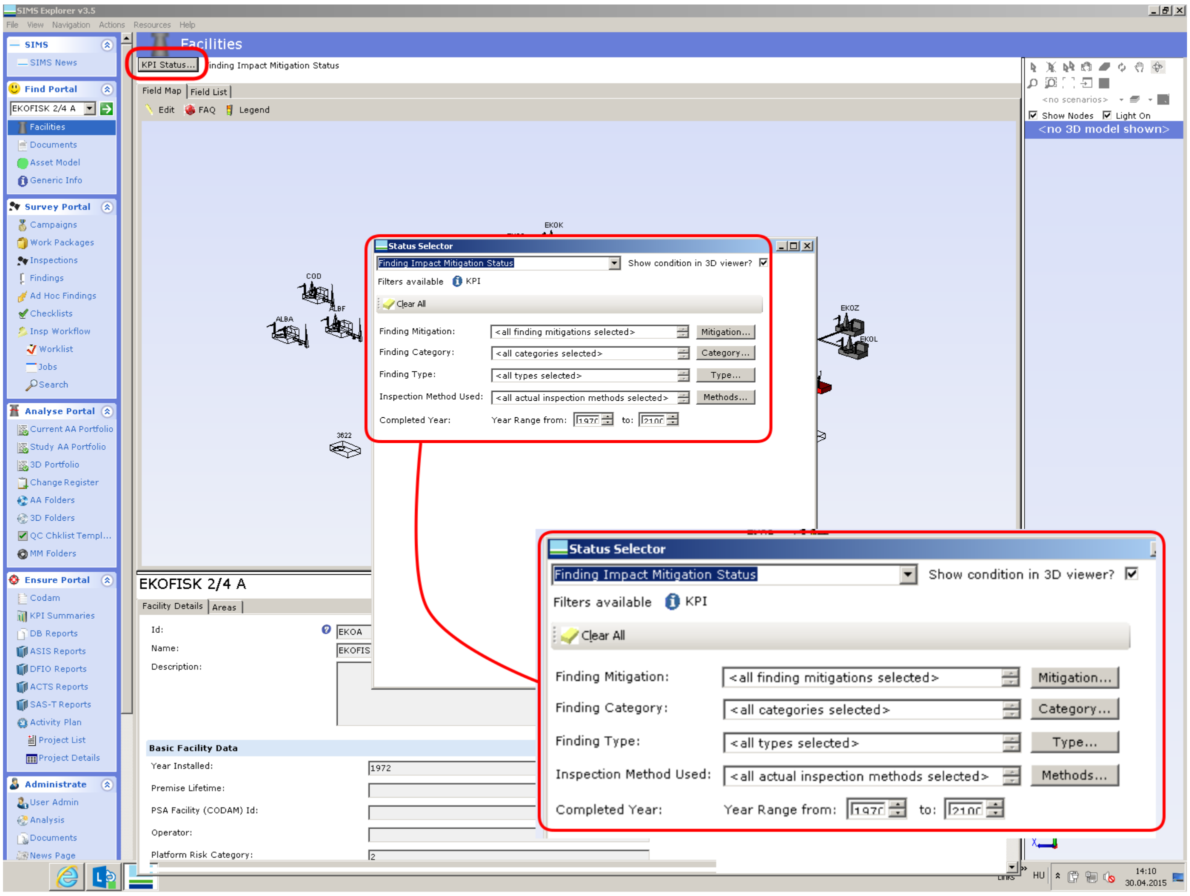
Premise Lifetime:

PSA Facility (CODAM) Id:

Operator:

Platform Risk Category: 2

Figure 2.3: Find portal – Field list tab



EKOFISK 2/4 A

Finding Impact Mitigation Status

Id: EKOA

Name: EKOFIS

Description:

Basic Facility Data

Year Installed: 1972

Premise Lifetime:

PSA Facility (CODAM) Id:

Operator:

Platform Risk Category: 2

Status Selector

Finding Impact Mitigation Status

Show condition in 3D viewer? ☑

Filters available KPI

Finding Mitigation: <all finding mitigations selected>

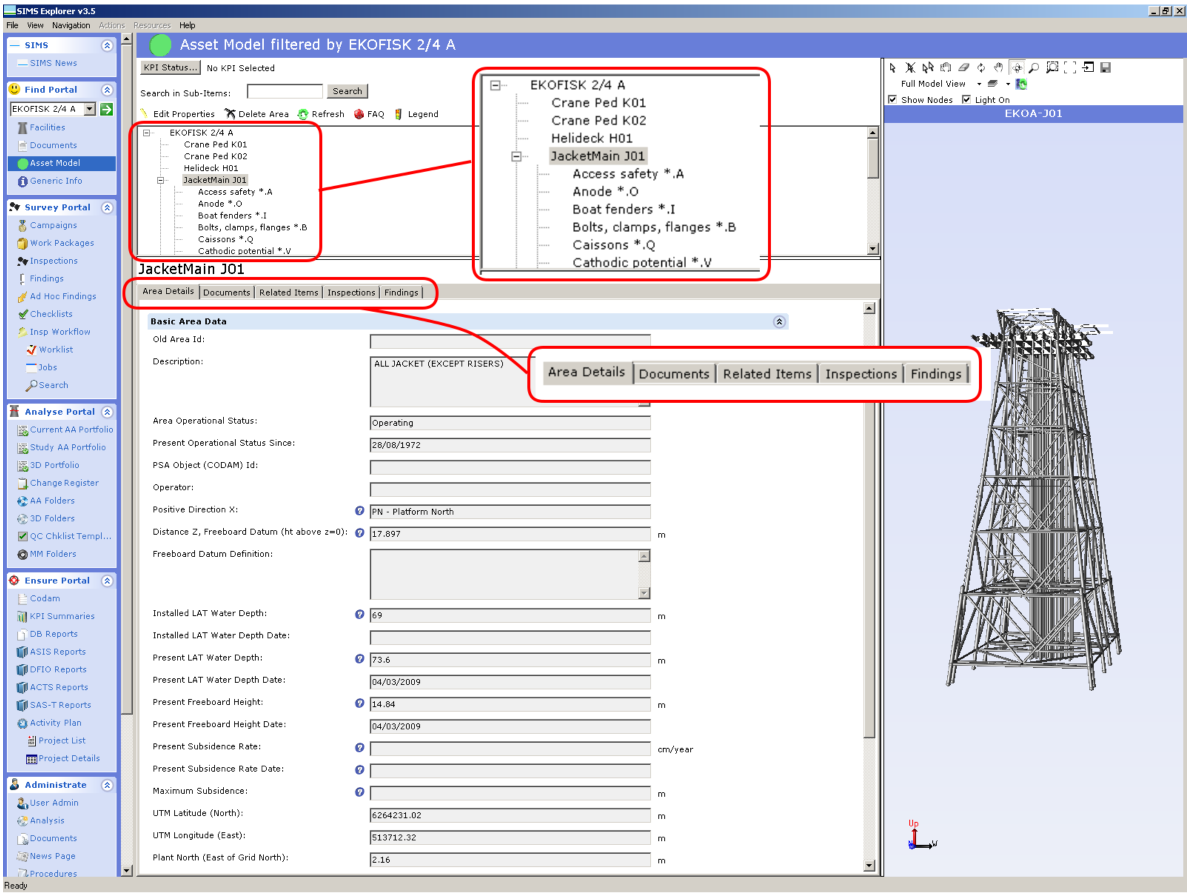
Finding Category: <all categories selected>

Finding Type: <all types selected>

Inspection Method Used: <all actual inspection methods selected>

Completed Year: Year Range from: 1970 to: 2100

Figure 2.4: Find portal – KPI status button



Asset Model filtered by EKOFISK 2/4 A

No KPI Selected

Search in Sub-Items:

- EKOFISK 2/4 A
  - Crane Ped K01
  - Crane Ped K02
  - Helideck H01
  - JacketMain J01
    - Access safety *.A
    - Anode *.O
    - Boat fenders *.I
    - Bolts, clamps, flanges *.B
    - Caissons *.Q
    - Cathodic potential *.V

JacketMain J01

Basic Area Data

Old Area Id:

Description: ALL JACKET (EXCEPT RISERS)

Area Operational Status: Operating

Present Operational Status Since: 28/08/1972

PSA Object (CODAM) Id:

Operator:

Positive Direction X: PN - Platform North

Distance Z, Freeboard Datum (ht above z=0): 17.897 m

Freeboard Datum Definition:

Installed LAT Water Depth: 69 m

Installed LAT Water Depth Date:

Present LAT Water Depth: 73.6 m

Present LAT Water Depth Date: 04/03/2009

Present Freeboard Height: 14.84 m

Present Freeboard Height Date: 04/03/2009

Present Subsidence Rate: cm/year

Present Subsidence Rate Date:

Maximum Subsidence: m

UTM Latitude (North): 6264231.02 m

UTM Longitude (East): 513712.32 m

Plant North (East of Grid North): 2.16 m

Figure 2.5: Find portal - Asset model with 3D viewer

C2.3 Survey portal

The Survey Portal enables access to inspection campaigns, work packages withing the campaigns and inspections within the work packages. Two tools (Campaigns and Work-packages) within the Survey portal have a so-called work-flow mode, where the default SIMS window disappears and the Task bar lists functions only typical for the given tool.

The *Campaigns tool* (Figure 2.6) is designed for the administration and management of inspection campaigns. The structuring method in SIMS for inspections is that the prescribed inspections are organized into campaigns (typically inspections within the same year), and campaigns are further structured down into work-packages which include inspections for a given facility in a given zone. The Campaigns tool (outside the work-flow mode) lists basic details about the campaign and linked documents. The structuring implies the way of creating and arranging inspections. First the inspections are created, so they are assigned to campaigns, finally the work packages are created inside the campaigns.

The *Work-packages tool*, similarly to the Campaigns tool, features a very typical SIMS screen (Figure 2.7), listing basic details. The work packages, similarly to many items in SIMS, are searchable.

One can enter the work-flow mode by double clicking the selected work-package, which opens at the *Details* window (Figure 2.8). It is possible to widen the range of details here, with e.g. documents (Figure 2.9).

In the *Inspections menu* (Figure 2.10) a series of information can be assigned to the inspection. The figure shows the Location tab, and how the position of the inspection is given is zoomed in the figure. It is possible to show the location in the 3D viewer window also. The inspections can be searched based on status, zones, inspection type or sources.

The findings can be recorded under the *Record findings menu*. The possible meta-data here assures that the finding is precisely described, can be traced to a campaign[1], can be linked to documents and location.

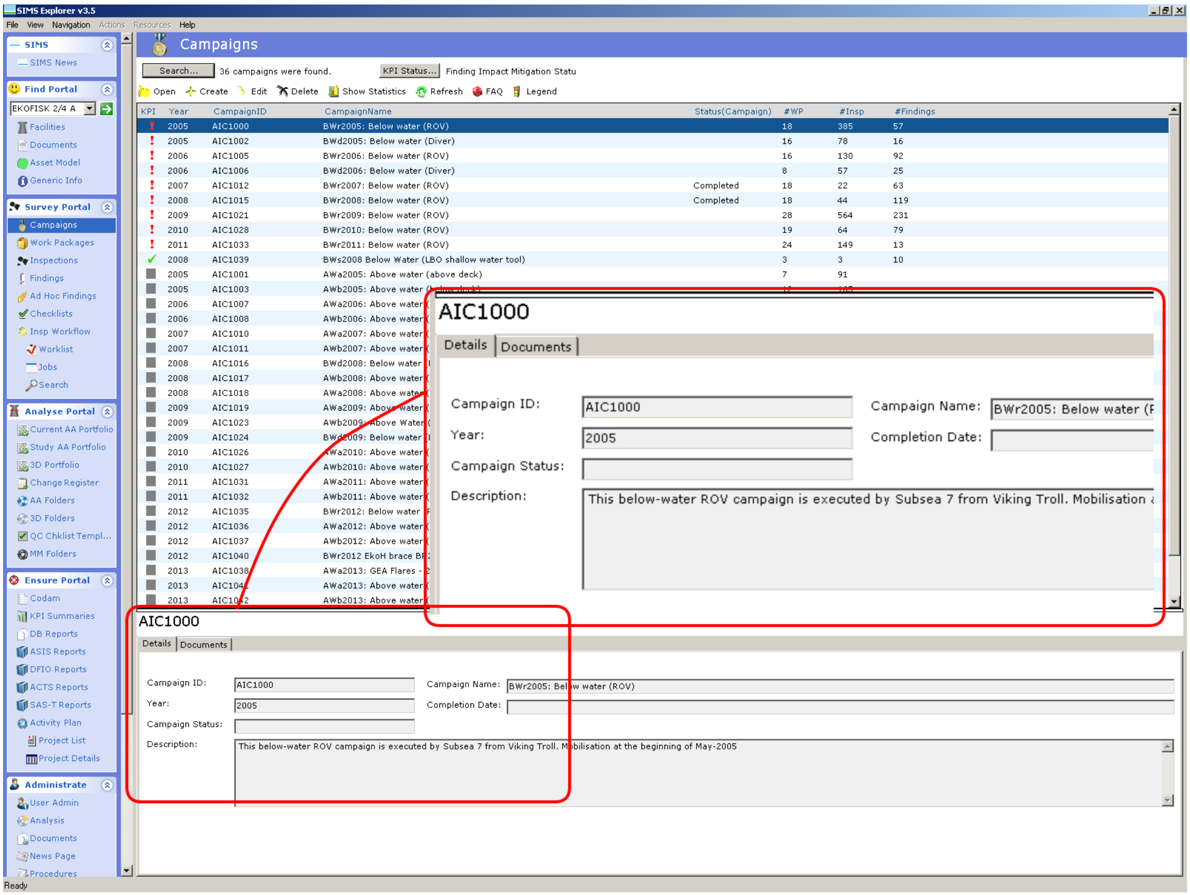
The findings are evaluated in the *Evaluate findings menu* after the finding has been recorded and was given a status “complete”. In this step the severity status is set or corrective action is initiated for the finding. It is also possible to decide if it is to be included in a Codam report. The linked asset model and mitigation can be given.

The *Findings tool* makes it possible display the condition of findings as well as to locate them in the 3D viewer.

The *Insp Workflow / Worklist tool* is design to track the jobs or tasks that are assigned to a given user. This way the progress of someone can be seen, as well as possible the reassign the responsibility to someone else if needed.

---

[1] It is possible to register ad-hoc findings also



36 campaigns were found.

Finding Impact Mitigation Statu

KPI	Year	CampaignID	CampaignName	Status(Campaign)	#WP	#Insp	#Findings
!	2005	AIC1000	BWr2005: Below water (ROV)		18	385	57
!	2005	AIC1002	BWd2005: Below water (Diver)		16	78	16
!	2006	AIC1005	BWr2006: Below water (ROV)		16	130	92
!	2006	AIC1006	BWd2006: Below water (Diver)		8	57	25
!	2007	AIC1012	BWr2007: Below water (ROV)	Completed	18	22	63
!	2008	AIC1015	BWr2008: Below water (ROV)	Completed	18	44	119
!	2009	AIC1021	BWr2009: Below water (ROV)		28	564	231
!	2010	AIC1028	BWr2010: Below water (ROV)		19	64	79
!	2011	AIC1033	BWr2011: Below water (ROV)		24	149	13
✓	2008	AIC1039	BWs2008 Below Water (LBO shallow water tool)		3	3	10
■	2005	AIC1001	AWa2005: Above water (above deck)		7	91	
■	2005	AIC1003	AWb2005: Above water (				
■	2006	AIC1007	AWa2006: Above water (				
■	2006	AIC1008	AWb2006: Above water (				
■	2007	AIC1010	AWa2007: Above water (				
■	2007	AIC1011	AWb2007: Above water (				
■	2008	AIC1016	BWd2008: Below water (				
■	2008	AIC1017	AWb2008: Above water (				
■	2008	AIC1018	AWa2008: Above water (				
■	2009	AIC1019	AWa2009: Above water (				
■	2009	AIC1023	AWb2009: Above Water (				
■	2009	AIC1024	BWd2009: Below water (				
■	2010	AIC1026	AWa2010: Above water (				
■	2010	AIC1027	AWb2010: Above water (				
■	2011	AIC1031	AWa2011: Above water (				
■	2011	AIC1032	AWb2011: Above water (				
■	2012	AIC1035	BWr2012: Below water				
■	2012	AIC1036	AWa2012: Above water (				
■	2012	AIC1037	AWb2012: Above water (				
■	2012	AIC1040	BWr2012 EkoH brace BR				
■	2013	AIC1038	AWa2013: GEA Flares - 2				
■	2013	AIC1041	AWa2013: Above water (				
■	2013	AIC1042	AWb2013: Above water (				

AIC1000

Campaign ID: AIC1000

Campaign Name: BWr2005: Below water (ROV)

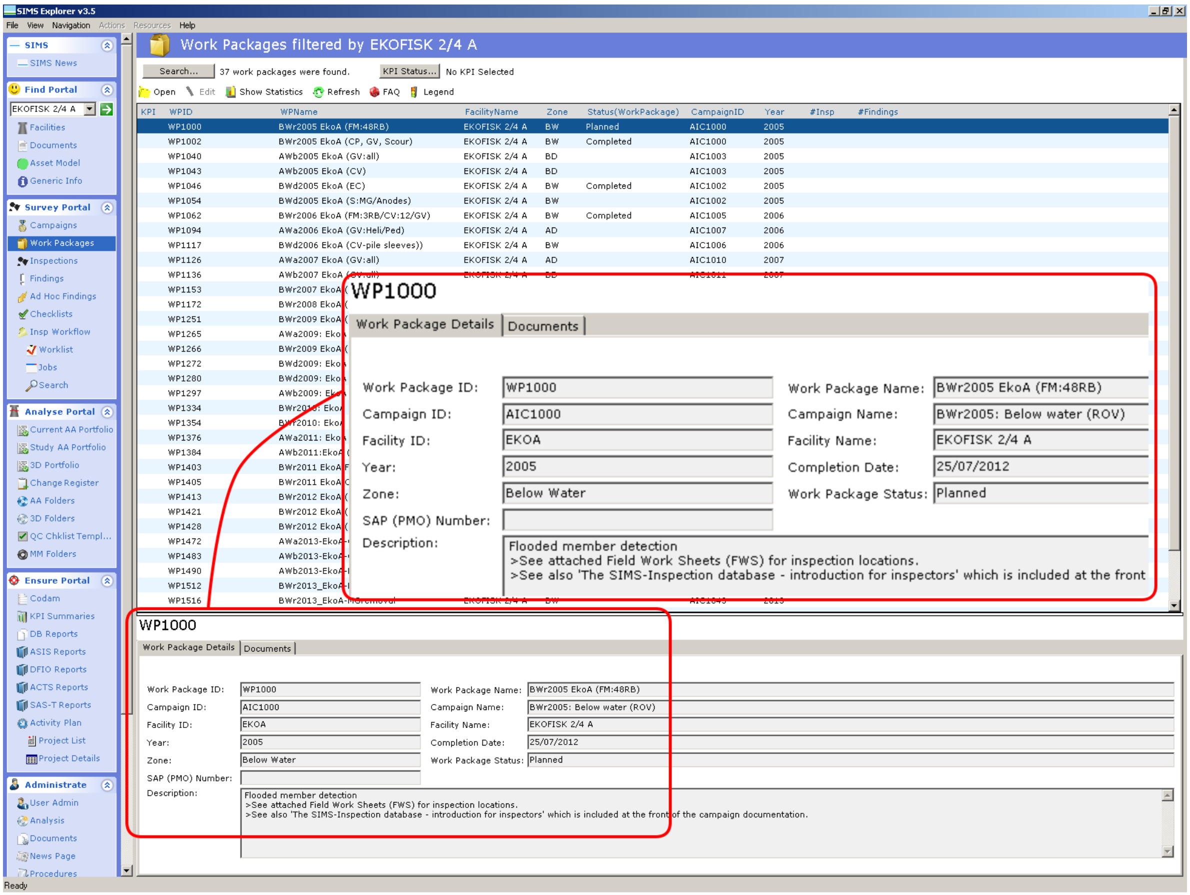
Year: 2005

Completion Date:

Campaign Status:

Description: This below-water ROV campaign is executed by Subsea 7 from Viking Troll. Mobilisation at the beginning of May-2005

Figure 2.6: Survey portal - Campaigns



37 work packages were found.

No KPI Selected

KPI	WPID	WPName	FacilityName	Zone	Status(WorkPackage)	CampaignID	Year	#Insp	#Findings
	WP1000	BWr2005 EkoA (FM:48RB)	EKOFISK 2/4 A	BW	Planned	AIC1000	2005		
	WP1002	BWr2005 EkoA (CP, GV, Scour)	EKOFISK 2/4 A	BW	Completed	AIC1000	2005		
	WP1040	AWb2005 EkoA (GV:all)	EKOFISK 2/4 A	BD		AIC1003	2005		
	WP1043	AWb2005 EkoA (CV)	EKOFISK 2/4 A	BD		AIC1003	2005		
	WP1046	BWd2005 EkoA (EC)	EKOFISK 2/4 A	BW	Completed	AIC1002	2005		
	WP1054	BWd2005 EkoA (S:MG/Anodes)	EKOFISK 2/4 A	BW		AIC1002	2005		
	WP1062	BWr2006 EkoA (FM:3RB/CV:12/GV)	EKOFISK 2/4 A	BW	Completed	AIC1005	2006		
	WP1094	AWa2006 EkoA (GV:Heli/Ped)	EKOFISK 2/4 A	AD		AIC1007	2006		
	WP1117	BWd2006 EkoA (CV-pile sleeves))	EKOFISK 2/4 A	BW		AIC1006	2006		
	WP1126	AWa2007 EkoA (GV:all)	EKOFISK 2/4 A	AD		AIC1010	2007		
	WP1136	AWb2007 EkoA							
	WP1153	BWr2007 EkoA (							
	WP1172	BWr2008 EkoA (							
	WP1251	BWr2009 EkoA (							
	WP1265	AWa2009: Eko							
	WP1266	BWr2009 EkoA (							
	WP1272	BWd2009: Eko							
	WP1280	BWd2009: Eko							
	WP1297	AWb2009: Eko							
	WP1334	BWr2010: Eko							
	WP1354	BWr2010: Eko							
	WP1376	AWa2011: Eko							
	WP1384	AWb2011:EkoA (							
	WP1403	BWr2011 EkoA F							
	WP1405	BWr2011 EkoA C							
	WP1413	BWr2012 EkoA (							
	WP1421	BWr2012 EkoA (							
	WP1428	BWr2012 EkoA (							
	WP1472	AWa2013-EkoA-							
	WP1483	AWb2013-EkoA-							
	WP1490	AWb2013-EkoA-							
	WP1512	BWr2013_EkoA-							
	WP1516	BWr2013_EkoA-							

WP1000

Work Package ID: WP1000

Work Package Name: BWr2005 EkoA (FM:48RB)

Campaign ID: AIC1000

Campaign Name: BWr2005: Below water (ROV)

Facility ID: EKOA

Facility Name: EKOFISK 2/4 A

Year: 2005

Completion Date: 25/07/2012

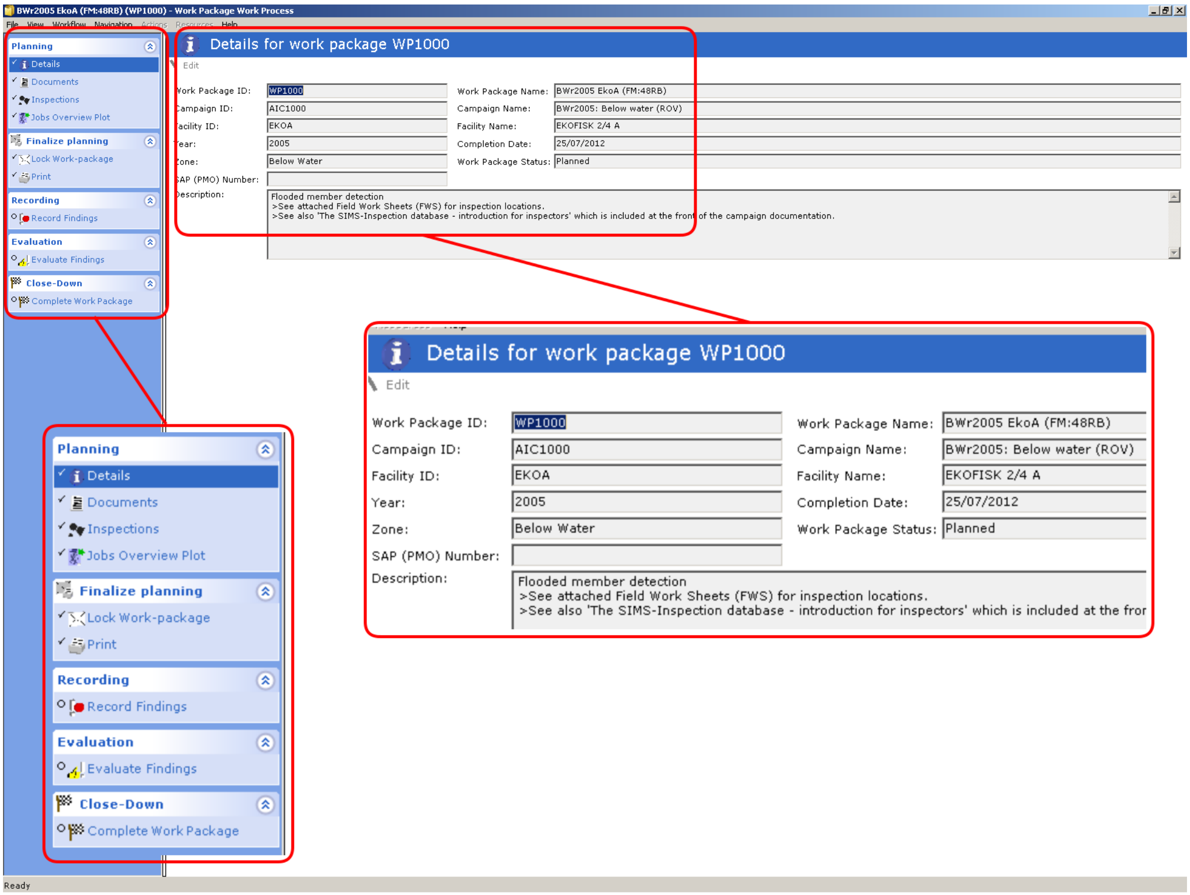
Zone: Below Water

Work Package Status: Planned

SAP (PMO) Number:

Description: Flooded member detection
>See attached Field Work Sheets (FWS) for inspection locations.
>See also 'The SIMS-Inspection database - introduction for inspectors' which is included at the front of the campaign documentation.

Figure 2.7: Survey portal - Work packages

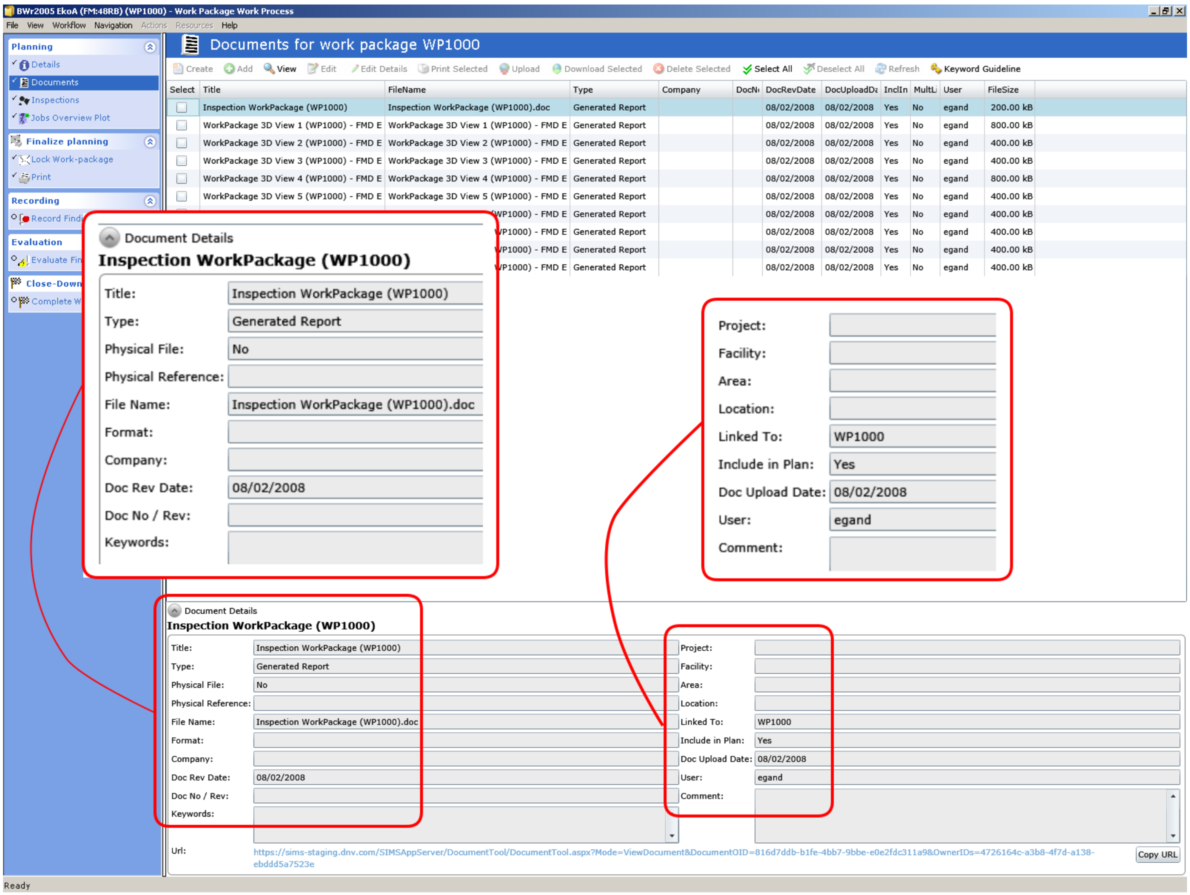


Details for work package WP1000

Work Package ID:	WP1000	Work Package Name:	BWr2005 EkoA (FM:48RB)
Campaign ID:	AIC1000	Campaign Name:	BWr2005: Below water (ROV)
Facility ID:	EKOA	Facility Name:	EKOFISK 2/4 A
Year:	2005	Completion Date:	25/07/2012
Zone:	Below Water	Work Package Status:	Planned
SAP (PMO) Number:			

Description:
Flooded member detection
>See attached Field Work Sheets (FWS) for inspection locations.
>See also 'The SIMS-Inspection database - introduction for inspectors' which is included at the front of the campaign documentation.

Figure 2.8: Survey portal – Work packages (work-flow) – Details



Documents for work package WP1000

Select	Title	FileName	Type	Company	DocN	DocRevDate	DocUploadDa	InclIn	MultLi	User	FileSize
☐	Inspection WorkPackage (WP1000)	Inspection WorkPackage (WP1000).doc	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	200.00 kB
☐	WorkPackage 3D View 1 (WP1000) - FMD E	WorkPackage 3D View 1 (WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	800.00 kB
☐	WorkPackage 3D View 2 (WP1000) - FMD E	WorkPackage 3D View 2 (WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
☐	WorkPackage 3D View 3 (WP1000) - FMD E	WorkPackage 3D View 3 (WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
☐	WorkPackage 3D View 4 (WP1000) - FMD E	WorkPackage 3D View 4 (WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	800.00 kB
☐	WorkPackage 3D View 5 (WP1000) - FMD E	WorkPackage 3D View 5 (WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
		WP1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
		P1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
		P1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB
		P1000) - FMD E	Generated Report			08/02/2008	08/02/2008	Yes	No	egand	400.00 kB

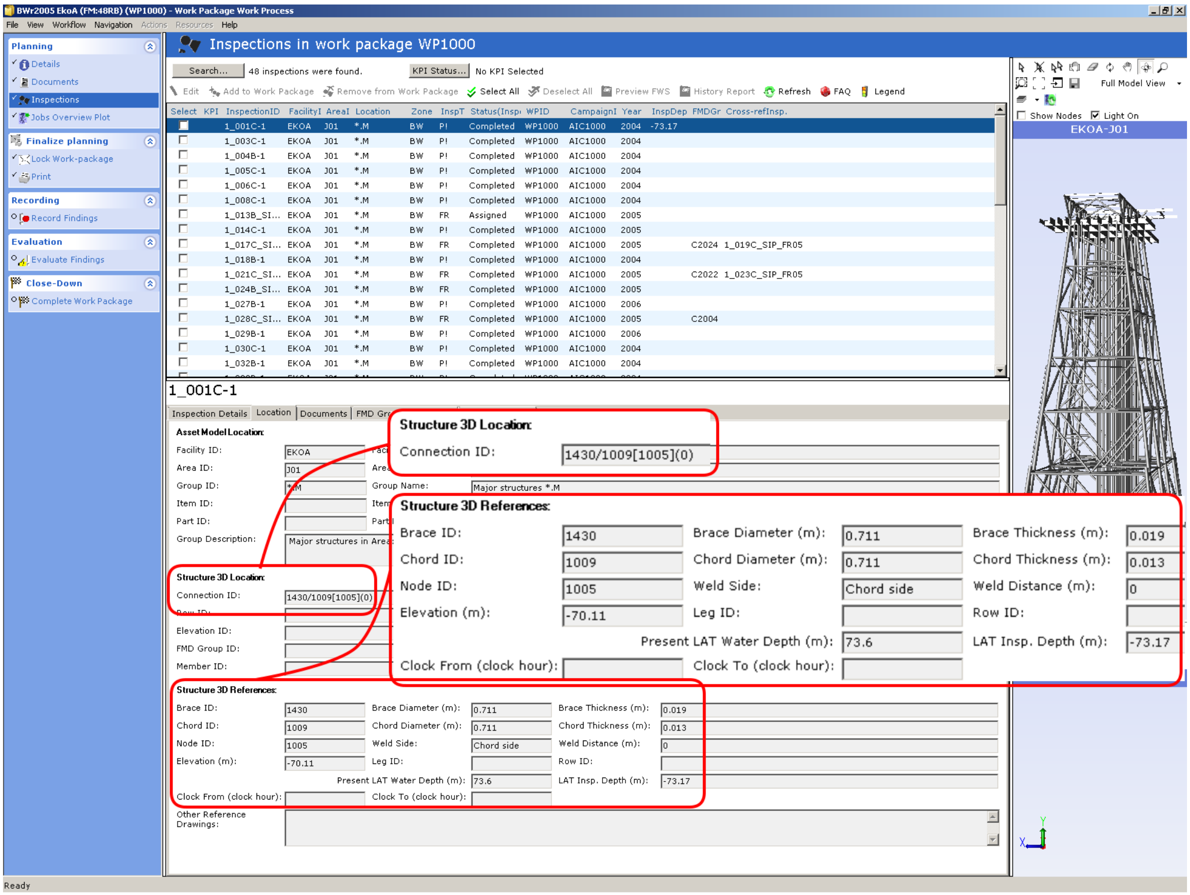
Document Details

Inspection WorkPackage (WP1000)

Title:	Inspection WorkPackage (WP1000)	Project:	
Type:	Generated Report	Facility:	
Physical File:	No	Area:	
Physical Reference:		Location:	
File Name:	Inspection WorkPackage (WP1000).doc	Linked To:	WP1000
Format:		Include in Plan:	Yes
Company:		Doc Upload Date:	08/02/2008
Doc Rev Date:	08/02/2008	User:	egand
Doc No / Rev:		Comment:	
Keywords:			

Url: https://sims-staging.dnv.com/SIMSAppServer/DocumentTool/DocumentTool.aspx?Mode=ViewDocument&DocumentOID=816d7ddb-b1fe-4bb7-9bbe-e0e2fdc311a9&OwnerIDs=4726164c-a3b8-4f7d-a138-ebddd5a7523e

Figure 2.9: Survey portal - Work packages (work-flow) – Documents



48 inspections were found.

No KPI Selected

Select	KPI	InspectionID	FacilityI	AreaI	Location	Zone	InspT	Status(Insp	WPID	CampaignI	Year	InspDep	FMDGr	Cross-refInsp.
☐		1_001C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004	-73.17		
☐		1_003C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_004B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_005C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_006C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_008C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_013B_SI...	EKOA	J01	*.M	BW	FR	Assigned	WP1000	AIC1000	2005			
☐		1_014C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2005			
☐		1_017C_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005		C2024	1_019C_SIP_FR05
☐		1_018B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_021C_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005		C2022	1_023C_SIP_FR05
☐		1_024B_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005			
☐		1_027B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2006			
☐		1_028C_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005		C2004	
☐		1_029B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2006			
☐		1_030C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_032B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			

1_001C-1

Asset Model Location:

Facility ID: EKOA

Area ID: J01

Group ID: *.M

Group Name: Major structures *.M

Item ID:

Part ID:

Group Description: Major structures in Area

Structure 3D Location:

Connection ID: 1430/1009[1005](0)

Elevation ID:

FMD Group ID:

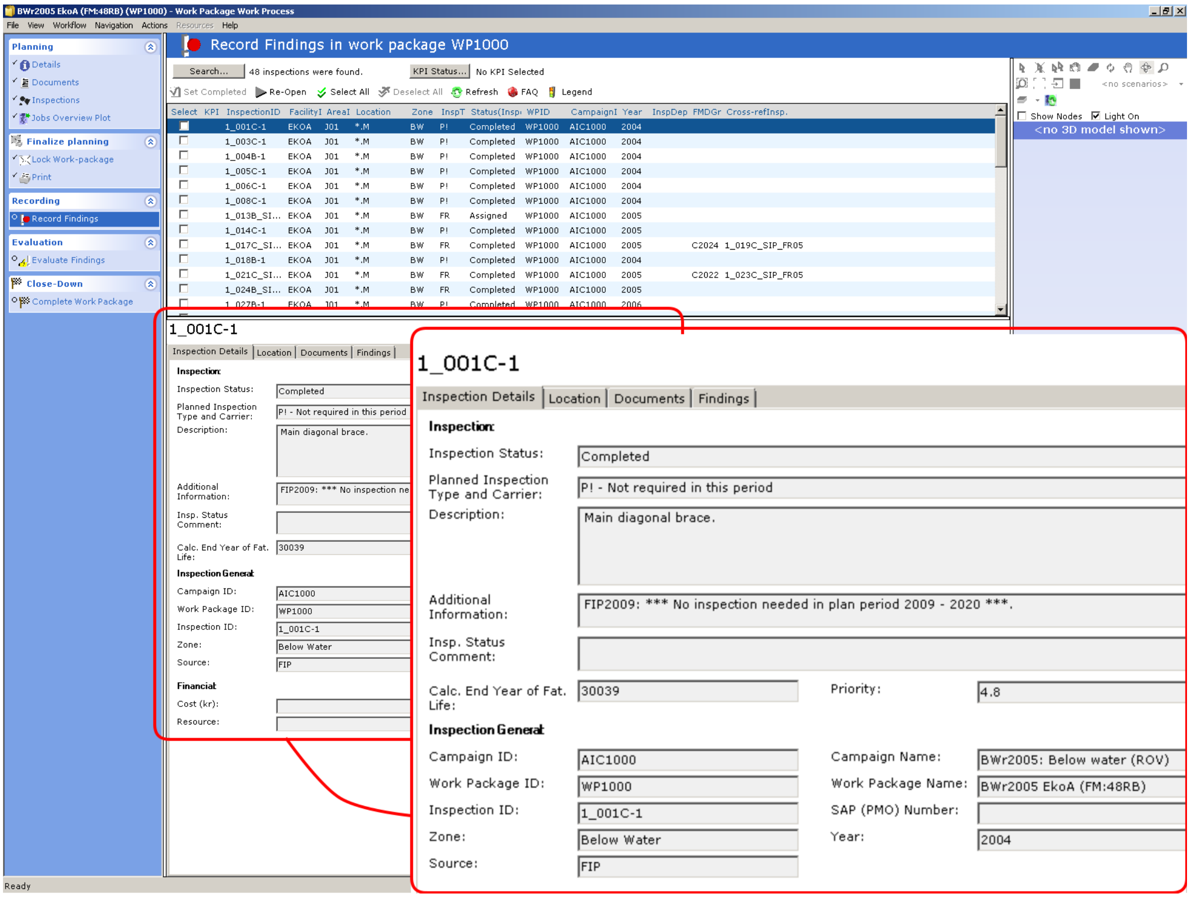
Member ID:

Structure 3D References:

Brace ID:	1430	Brace Diameter (m):	0.711	Brace Thickness (m):	0.019
Chord ID:	1009	Chord Diameter (m):	0.711	Chord Thickness (m):	0.013
Node ID:	1005	Weld Side:	Chord side	Weld Distance (m):	0
Elevation (m):	-70.11	Leg ID:		Row ID:	
		Present LAT Water Depth (m):	73.6	LAT Insp. Depth (m):	-73.17
Clock From (clock hour):		Clock To (clock hour):			

Other Reference Drawings:

Figure 2.10: Survey portal - Work packages (work-flow) – Inspections



48 inspections were found.

No KPI Selected

Select	KPI	InspectionID	FacilityI	AreaI	Location	Zone	InspT	Status(Insp	WPID	CampaignI	Year	InspDep	FMDGr	Cross-refInsp.
☐		1_001C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_003C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_004B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_005C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_006C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_008C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_013B_SI...	EKOA	J01	*.M	BW	FR	Assigned	WP1000	AIC1000	2005			
☐		1_014C-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2005			
☐		1_017C_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005		C2024	1_019C_SIP_FR05
☐		1_018B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2004			
☐		1_021C_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005		C2022	1_023C_SIP_FR05
☐		1_024B_SI...	EKOA	J01	*.M	BW	FR	Completed	WP1000	AIC1000	2005			
☐		1_027B-1	EKOA	J01	*.M	BW	P!	Completed	WP1000	AIC1000	2006			

1_001C-1

Inspection:

Inspection Status: Completed

Planned Inspection Type and Carrier: P! - Not required in this period

Description: Main diagonal brace.

Additional Information: FIP2009: *** No inspection needed in plan period 2009 - 2020 ***.

Insp. Status Comment:

Calc. End Year of Fat. Life: 30039

Priority: 4.8

Inspection General:

Campaign ID:	AIC1000	Campaign Name:	BWr2005: Below water (ROV)
Work Package ID:	WP1000	Work Package Name:	BWr2005 EkoA (FM:48RB)
Inspection ID:	1_001C-1	SAP (PMO) Number:	
Zone:	Below Water	Year:	2004
Source:	FIP		

Financial:

Cost (kr):

Resource:

Figure 2.11: Survey portal - Work packages (work-flow) – Record findings

C2.4 Analysis portal

The purpose of the Analysis portal (SIMS-a) is to enable storing, retrieving and managing computer models of structural assets. As it is written in the main part of the thesis the models are stored as 'As-is' Assurance models (AAm) which contain the geometry, permanent and variable loads as well as the scripts to make the analyses run. How much the AAm models represent the as-is condition is reflected in the AAm status. How much the results of the analyses comply with regulations is expressed in the AAa status. In addition there are two more statuses, the AAQC and the AASAS status which compile into the AAc status, which is the highest level compliance status for the 'As-is' Assurance models. The AAa status and the AAQC status are manually set by the responsibly for structural analysis, while the AASAS (Figure 2.15) is a program generated list.

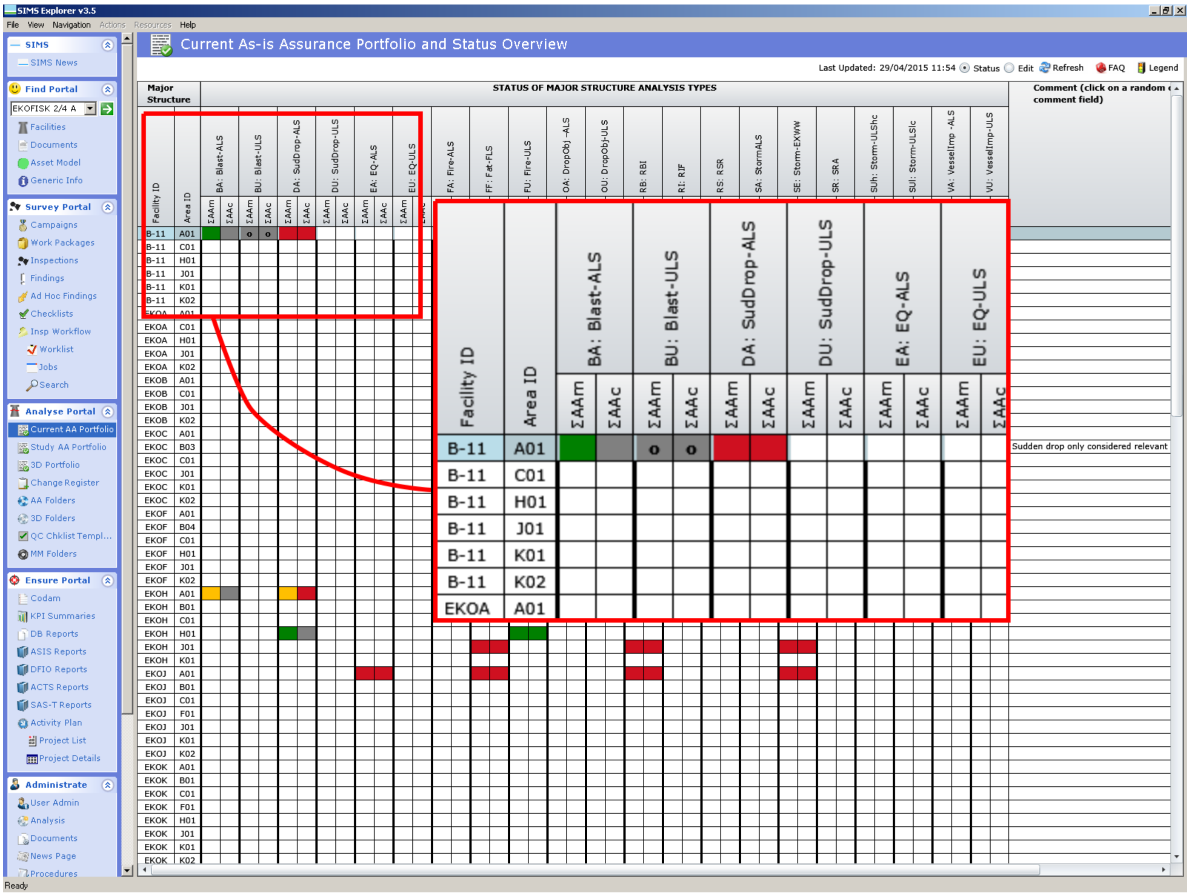
The models are stored in so called *AA folders* (Figure 2.15) which provide the function of maintaining and archiving models connected to a certain Major Structure Area of a facility (see section 2.2 for the list of areas). The 3D viewer model have their own folders too. All the AA folders receive an Facility ID (FID). It is possible to define a child / parent relation between the models, and the interconnectedness defined by the child / parent relations is defined by referring to the appropriate FID.

The AA folders have tags that define the analysis type (storm, fatigue, ULS, ALS); the used software; the responsible persons for the analysis; the title and revision of the report that documents the model and analysis.

In Figure 2.12 and Figure 2.13 the *Current AA portfolio tool* is shown, first in status, afterwards in edit mode. The status mode gives a very high level overview of the AAm and AAc statuses of the different Major Structure Areas stored in the SIMS system. It is a matrix where all the needed analysis types are listed in the top row (Blast-ULS, Blast-ALS, etc.) and it is color-coded cells that show status for a given Facility / Area.

In the edit mode figure (Figure 2.13) the area zoomed in shows how the necessity for a model for a given area and hazard can be defined. It is a drop-down menu for each cell where the user can select if the model/analysis is required. In the figures it can be seen that SIMS contains similar portfolio overview windows for study analyses and 3D viewer models also (on the left, under the *Current AA Portfolio* menu).

In Figure 2.14 the *Change register tool* of the Analyse portal is shown. This is where the different changes can be registered, as well as AA folders and 3D viewer folders can be linked to the change which signals that these being affected by the change. The source of the change can be a finding of corrosion or crack, a planned modification, revised environmental loads, revised regulatory requirements or damage (from boat collision or dropped object). In Figure 2.14 the highlighted area shows the meta-data that can be provided to give a description of the change. It can also be seen that in the tabs at the top documents, AA folders and 3D folders can be linked to the change right away.



SIMS Explorer v3.5

Current As-is Assurance Portfolio and Status Overview

Last Updated: 29/04/2015 11:54 ● Status ○ Edit Refresh FAQ Legend

Major Structure

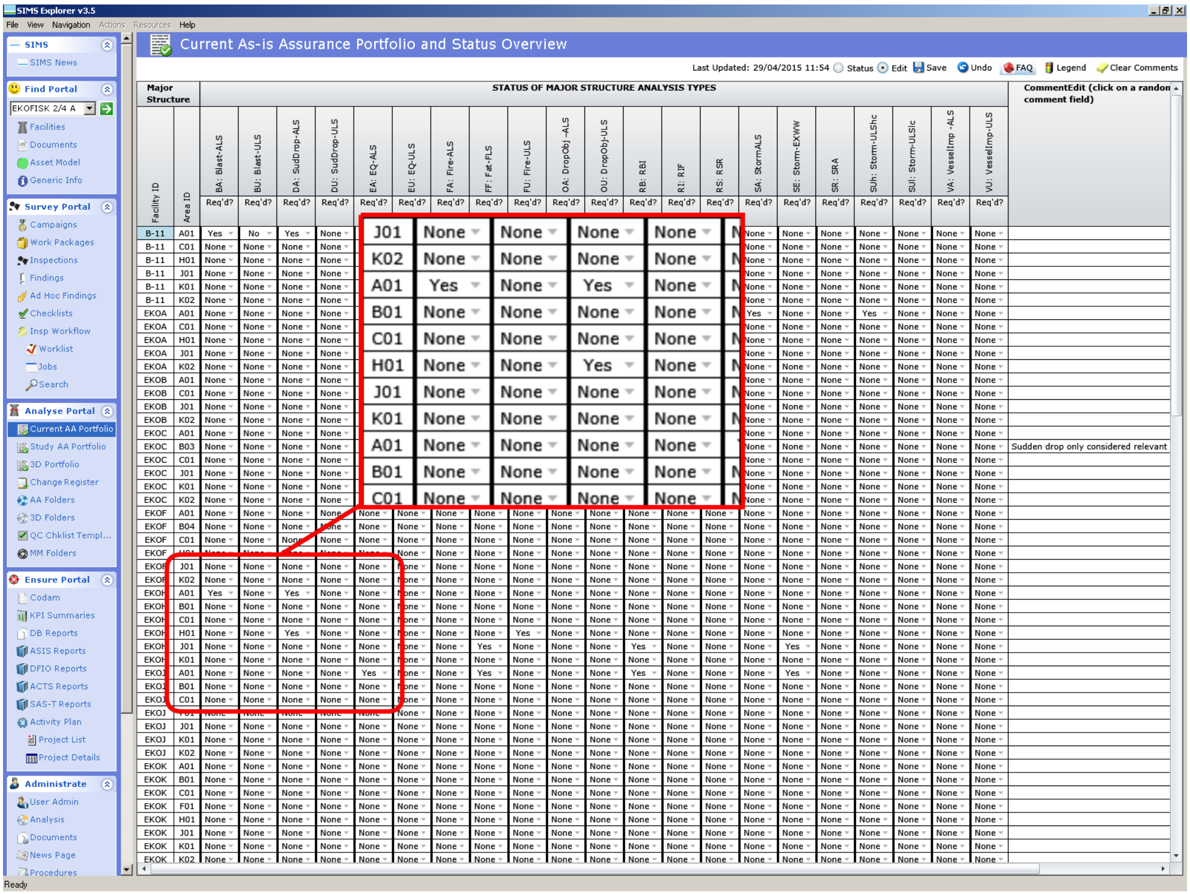
STATUS OF MAJOR STRUCTURE ANALYSIS TYPES

Comment (click on a random comment field)

Facility ID	Area ID	BA: Blast-ALS		BU: Blast-ULS		DA: SudDrop-ALS		DU: SudDrop-ULS		EA: EQ-ALS		EU: EQ-ULS	
		ΣAAm	ΣAAc	ΣAAm	ΣAAc	ΣAAm	ΣAAc	ΣAAm	ΣAAc	ΣAAm	ΣAAc	ΣAAm	ΣAAc
B-11	A01	🟩	▨	o	o	🟥	🟥						
B-11	C01												
B-11	H01												
B-11	J01												
B-11	K01												
B-11	K02												
EKOA	A01												

Sudden drop only considered relevant

Figure 2.12: Analysis portal - Current AA portfolio



SIMS Explorer v3.5

Current As-is Assurance Portfolio and Status Overview

Last Updated: 29/04/2015 11:54 ○ Status ● Edit Save Undo FAQ Legend Clear Comments

Major Structure

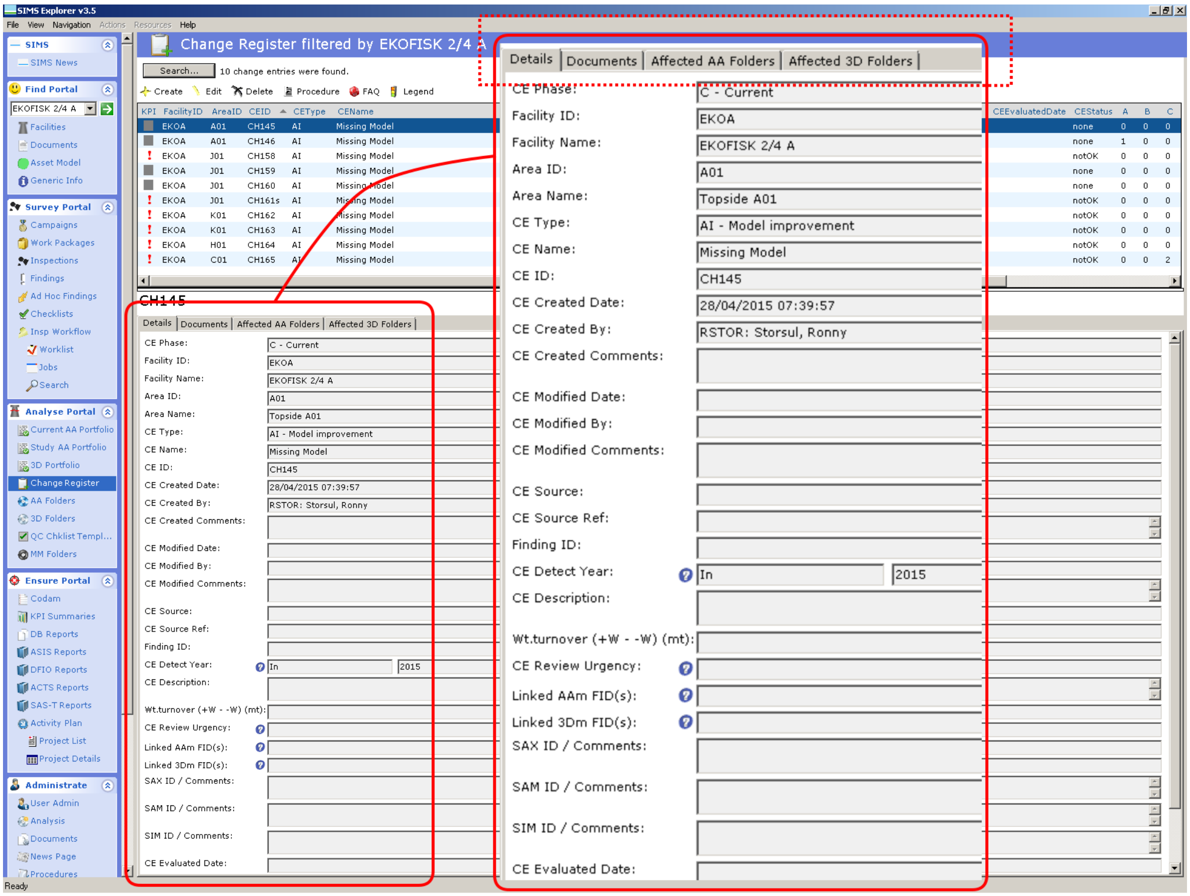
STATUS OF MAJOR STRUCTURE ANALYSIS TYPES

CommentEdit (click on a random comment field)

J01	None	None	None	None
K02	None	None	None	None
A01	Yes	None	Yes	None
B01	None	None	None	None
C01	None	None	None	None
H01	None	None	Yes	None
J01	None	None	None	None
K01	None	None	None	None
A01	None	None	None	None
B01	None	None	None	None
C01	None	None	None	None

Sudden drop only considered relevant

Figure 2.13: Analysis portal - Current AA portfolio - Edit mode



Change Register filtered by EKOFISK 2/4 A

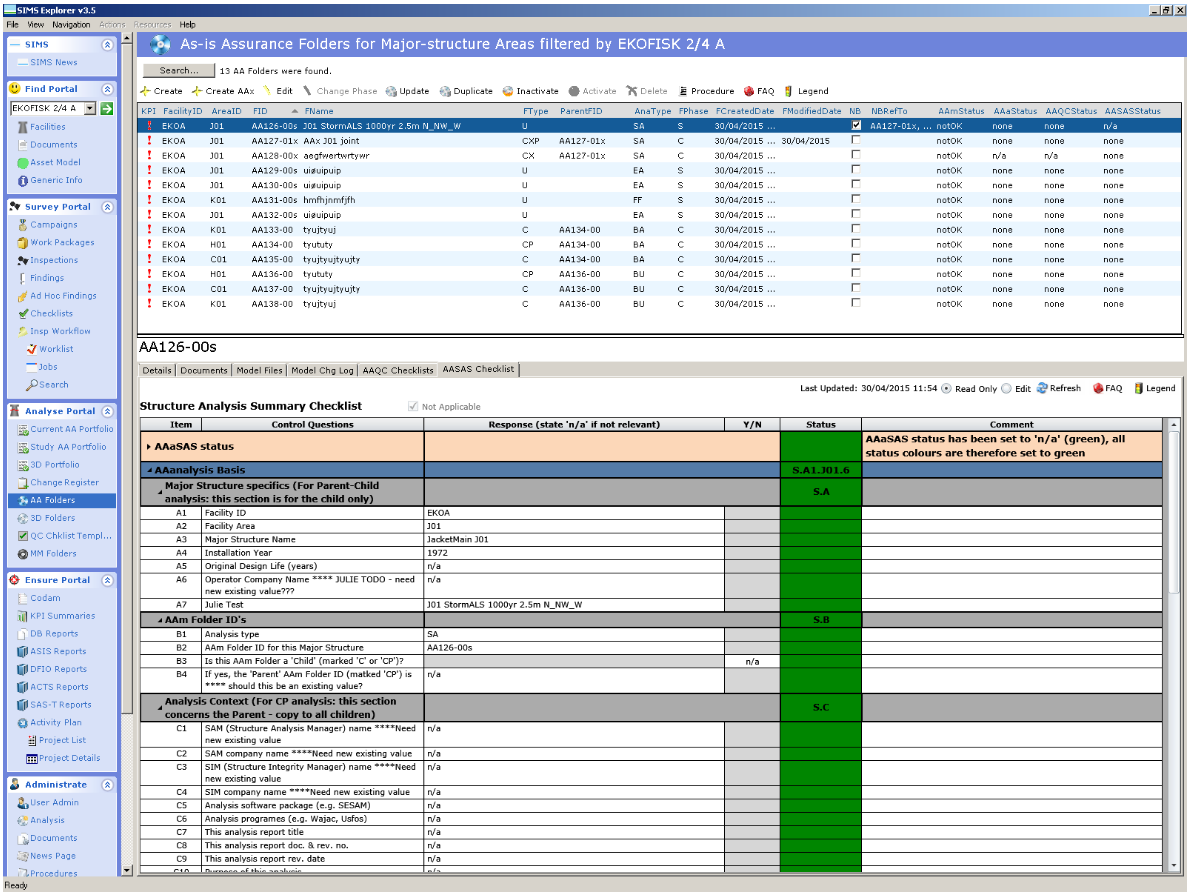
10 change entries were found.

KPI	FacilityID	AreaID	CEID	CEType	CEName	CEEvaluatedDate	CEStatus	A	B	C
■	EKOA	A01	CH145	AI	Missing Model		none	0	0	0
■	EKOA	A01	CH146	AI	Missing Model		none	1	0	0
!	EKOA	J01	CH158	AI	Missing Model		notOK	0	0	0
■	EKOA	J01	CH159	AI	Missing Model		none	0	0	0
■	EKOA	J01	CH160	AI	Missing Model		none	0	0	0
!	EKOA	J01	CH161s	AI	Missing Model		notOK	0	0	0
!	EKOA	K01	CH162	AI	Missing Model		notOK	0	0	0
!	EKOA	K01	CH163	AI	Missing Model		notOK	0	0	0
!	EKOA	H01	CH164	AI	Missing Model		notOK	0	0	0
!	EKOA	C01	CH165	AI	Missing Model		notOK	0	0	2

CH145

CE Phase:	C - Current
Facility ID:	EKOA
Facility Name:	EKOFISK 2/4 A
Area ID:	A01
Area Name:	Topside A01
CE Type:	AI - Model improvement
CE Name:	Missing Model
CE ID:	CH145
CE Created Date:	28/04/2015 07:39:57
CE Created By:	RSTOR: Storsul, Ronny
CE Created Comments:	
CE Modified Date:	
CE Modified By:	
CE Modified Comments:	
CE Source:	
CE Source Ref:	
Finding ID:	
CE Detect Year:	In 2015
CE Description:	
Wt.turnover (+W - -W) (mt):	
CE Review Urgency:	
Linked AAm FID(s):	
Linked 3Dm FID(s):	
SAX ID / Comments:	
SAM ID / Comments:	
SIM ID / Comments:	
CE Evaluated Date:	

Figure 2.14: Analysis portal - Change register



As-is Assurance Folders for Major-structure Areas filtered by EKOFISK 2/4 A

13 AA Folders were found.

KPI	FacilityID	AreaID	FID	FName	FType	ParentFID	AnaType	FPhase	FCreatedDate	FModifiedDate	NB	NBRefTo	AAmStatus	AAaStatus	AAQCStatus	AASASStatus
!	EKOA	J01	AA126-00s	J01 StormALS 1000yr 2.5m N_NW_W	U		SA	S	30/04/2015 ...		☑	AA127-01x, ...	notOK	none	none	n/a
!	EKOA	J01	AA127-01x	AAx J01 joint	CXP	AA127-01x	SA	C	30/04/2015 ...	30/04/2015	☐		notOK	none	none	none
!	EKOA	J01	AA128-00x	aegfwertwrtywr	CX	AA127-01x	SA	C	30/04/2015 ...		☐		notOK	n/a	n/a	none
!	EKOA	J01	AA129-00s	uiøuipuip	U		EA	S	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	J01	AA130-00s	uiøuipuip	U		EA	S	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	K01	AA131-00s	hmfhjnmfjfh	U		FF	S	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	J01	AA132-00s	uiøuipuip	U		EA	S	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	K01	AA133-00	tyujtyuj	C	AA134-00	BA	C	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	H01	AA134-00	tyututy	CP	AA134-00	BA	C	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	C01	AA135-00	tyujtyujtyujty	C	AA134-00	BA	C	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	H01	AA136-00	tyututy	CP	AA136-00	BU	C	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	C01	AA137-00	tyujtyujtyujty	C	AA136-00	BU	C	30/04/2015 ...		☐		notOK	none	none	none
!	EKOA	K01	AA138-00	tyujtyuj	C	AA136-00	BU	C	30/04/2015 ...		☐		notOK	none	none	none

AA126-00s

Last Updated: 30/04/2015 11:54 ● Read Only ○ Edit

Structure Analysis Summary Checklist ☑ Not Applicable

Item	Control Questions	Response (state 'n/a' if not relevant)	Y/N	Status	Comment
AAaSAS status					**AAaSAS status has been set to 'n/a' (green), all status colours are therefore set to green**
AAanalysis Basis				**S.A1.J01.6**	
Major Structure specifics (For Parent-Child analysis: this section is for the child only)				**S.A**	
A1	Facility ID	EKOA			
A2	Facility Area	J01			
A3	Major Structure Name	JacketMain J01			
A4	Installation Year	1972			
A5	Original Design Life (years)	n/a			
A6	Operator Company Name **** JULIE TODO - need new existing value???	n/a			
A7	Julie Test	J01 StormALS 1000yr 2.5m N_NW_W			
AAm Folder ID's				**S.B**	
B1	Analysis type	SA			
B2	AAm Folder ID for this Major Structure	AA126-00s			
B3	Is this AAm Folder a 'Child' (marked 'C' or 'CP')?		n/a		
B4	If yes, the 'Parent' AAm Folder ID (matked 'CP') is **** should this be an existing value?	n/a			
Analysis Context (For CP analysis: this section concerns the Parent - copy to all children)				**S.C**	
C1	SAM (Structure Analysis Manager) name ****Need new existing value	n/a			
C2	SAM company name ****Need new existing value	n/a			
C3	SIM (Structure Integrity Manager) name ****Need new existing value	n/a			
C4	SIM company name ****Need new existing value	n/a			
C5	Analysis software package (e.g. SESAM)	n/a			
C6	Analysis programes (e.g. Wajac, Usfos)	n/a			
C7	This analysis report title	n/a			
C8	This analysis report doc. & rev. no.	n/a			
C9	This analysis report rev. date	n/a			

Figure 2.15: Analysis portal - AA folders with AASAS checklist

C2.5 Ensure portal

The *CODAM tool* in the Ensure portal is used for issuing standardized, generated reports to the Petroleum Safety Authority (PSA). It is controlled within SIMS which findings will be included in the CODAM report by an attribute status (“send to codam” = yes). The *DB Reports tool* has been programmed to enable the creation of customer specific predefined standard reports.

The *KPI summaries tool* in Figure 2.16 shows a Structure Integrity Scorecard page that allows the user to see an overall view of the integrity of the facility at a top level. It will provide information on number of red and yellow flags in the SIMS database for current year as well as earlier year. It further provides trending on how the condition is in current year compared to earlier years, i.e. are the number of issues that needs attention reduced or increased compared to earlier years.

The other reports that can be generated here are the *ASIS report* which are usually generated at the end of a year to provide and integrity performance overview at both high or detailed levels. The other reports available are Analysis Change Task Summary (ACT), Structure Condition Anomaly Summary (SCA), Design, Fabrication, Installation, Operation Resumé (DFIO), Structure Analysis Summary (SAS).

The *Activity Plan tool* in Figure 2.17 is a project manager tool which is tailor made for SIMS. The structure of defineable items is Program / Project / Task. It is possible to view a Gantt diagram.

C2.6 Administrate

In the Administrative portal not all functions are available for all users. E.g. functions that define user access rights can only be used by people who have elevated rights.

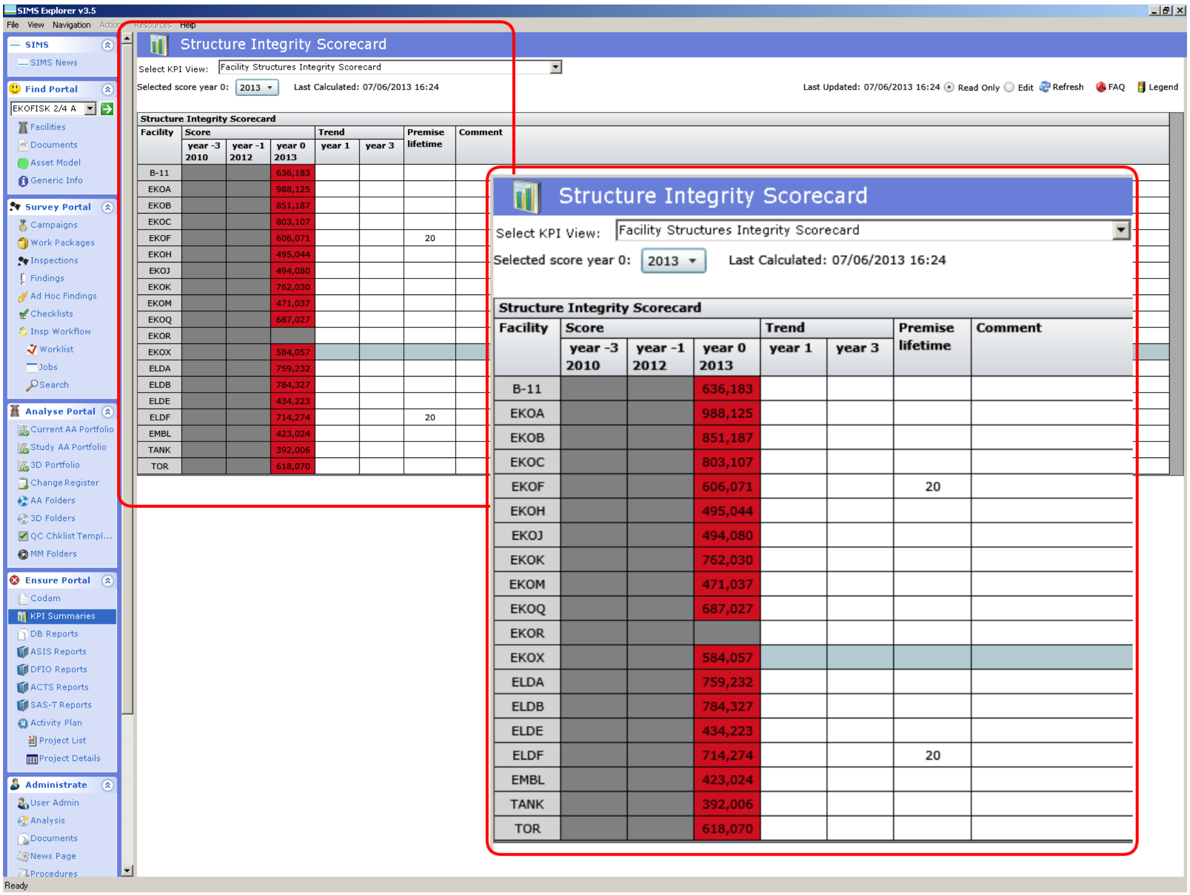
It is possible here to set the contents of the SIMS News, possible to define templates for checklists, input answers to local frequently asked questions (FAQ) that are typical for a given function.

The portal deals with the 'bulk' import functions of SIMS too. It is possible to make FMD group, 3D viewer and asset group imports.

The definition of the FMD group is that a structural member in real life may have to be modeled by several members in a computer model. An FMD group holds these members together, hence a flooded member detection on one of the members can trigger an internal fill condition status on other computer model members too.

As it was mentioned earlier the 3D viewer models are similar to the structural analysis models without loads. An internal module of SIMS can display the models within SIMS and provide various information in the 3D viewer screen. E.g. color-code members based on member fill condition status or show which member an inspection (finding) is linked to.

The Asset group is a set of members and nodes that constitute a portion of the 3D view model, e.g. jacket, risers, boat bumpers, elevation or row (the same as what Major Structure Area is). The reason for having asset groups is the have a better way of diverse display options in the 3D viewer, e.g. to be able to display only a certain, selected part of the structure and hide other parts which would necessarily complicate the display.



Structure Integrity Scorecard

Select KPI View: Facility Structures Integrity Scorecard

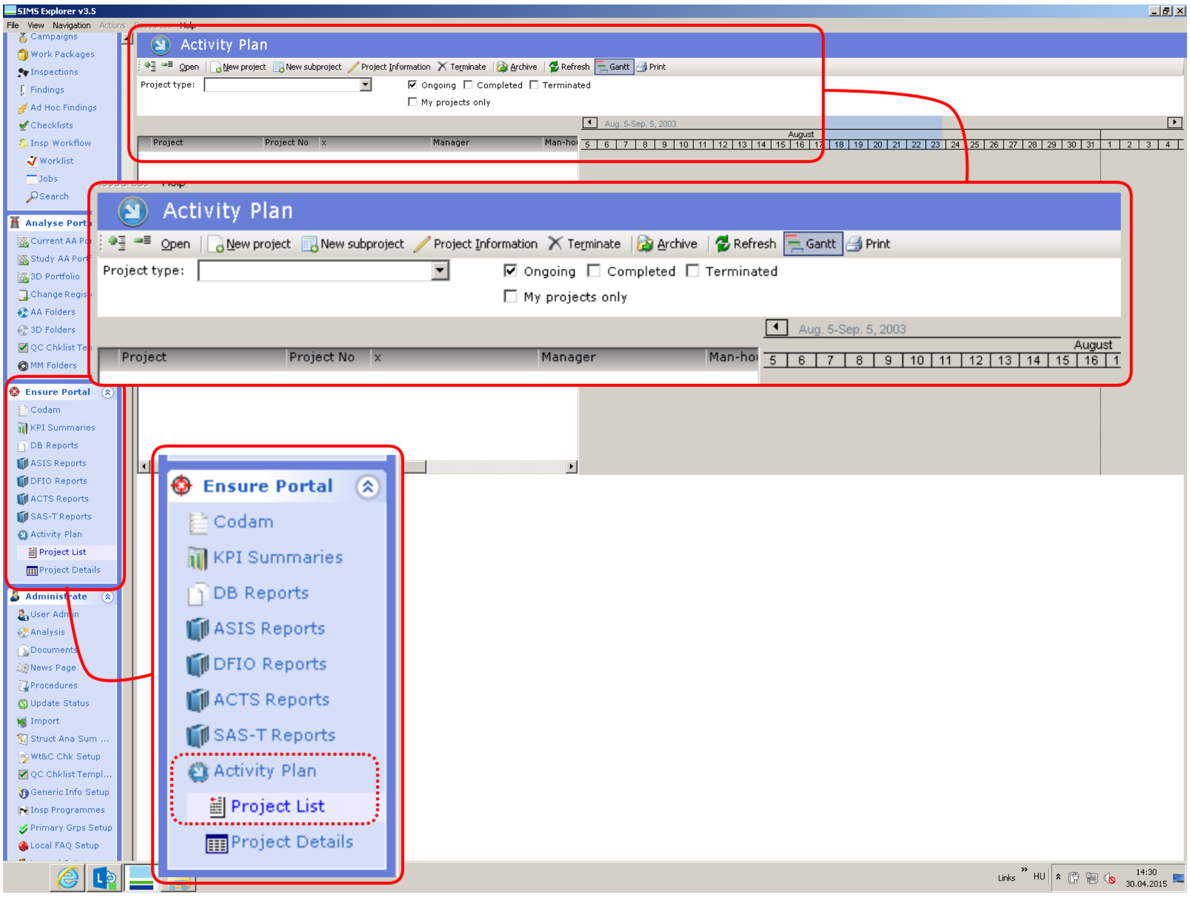
Selected score year 0: 2013 Last Calculated: 07/06/2013 16:24

Last Updated: 07/06/2013 16:24

Structure Integrity Scorecard

Facility	Score			Trend		Premise lifetime	Comment
	year -3 2010	year -1 2012	year 0 2013	year 1	year 3		
B-11			636,183				
EKOA			988,125				
EKOB			851,187				
EKOC			803,107				
EKOF			606,071			20	
EKOH			495,044				
EKOJ			494,080				
EKOK			762,030				
EKOM			471,037				
EKOQ			687,027				
EKOR							
EKOX			584,057				
ELDA			759,232				
ELDB			784,327				
ELDE			434,223				
ELDF			714,274			20	
EMBL			423,024				
TANK			392,006				
TOR			618,070				

Figure 2.16: Ensure portal - KPI summaries



Activity Plan

Project type:

☑ Ongoing ☐ Completed ☐ Terminated

☐ My projects only

Aug. 5-Sep. 5, 2003

Figure 2.17: Ensure portal - Activity plan

C3 References

/1/ DNV Software. Structure integrity management systems SIMS User Manual. Version 3.3. 2012.