BOLTED JOINTS

Study on bolt incidents

Petroleum Safety Authority

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Objective:
The aim of the project requested by PSA was to give an updated status regarding use of and incidents with bolts, and to give recommendations on potential development needs to reduce risks.

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1 EXECUTIVE SUMMARY

The Petroleum Safety Authority (PSA) has requested a project study to give an updated status regarding use of and incidents with bolts, and to give recommendations on potential development needs to reduce risks.

DNV GL has reviewed PSA's Incidents database ("Hendelsesdatabasen") and available Investigation reports ("Granskningsrapporter"). In addition, DNV GL's learnings from numerous failure investigations of bolted connections were utilised by DNV GL experts, as well as other referenced documents. In that respect, DNV GL has utilised and adapted a search engine with the objective to identify incidents associated with bolted joints in the Norwegian oil and gas industry, and to obtain trending regarding causes of these incidents.

The Incidents database is a database where all incidents reported by the operators to PSA are recorded. It is therefore the largest collection of incidents gathered in one database in Norway and contains a total of 12,156 records (as per May 2018) and covers the time period from 2000 to May 2018. 331 incidents were found to be bolt related and four of the received investigation reports refers to bolts. In addition, certain review reports were also included as data sources to demonstrate that any data source can easily be added to the search engine.

A review of incidents related to bolts amounts to 331 occurrences, which is approximately 3% of the total number of reported incidents. Of these, 2 and 79 incidents have been classified as "with high potential" ("Stort potensial") and as "serious" ("Alvorlig"), respectively. This amounts to less than 1% of the total reported incidents.

For incidents related to bolts, dropped objects and work accidents are the dominating consequence categories, while un-ignited hydrocarbon incidents, crane related incidents and "other" are also frequently registered. Incidents related to bolts appear to be more frequent in areas for "drilling and well" ("bore og brønn") and "utility systems" ("hjelpe og støttesystemer").

It has been difficult to find any trends related to failure mechanisms/root causes of the reported incidents, since the Incidents database focuses on HSE consequences and contain limited information regarding the technical root causes.

To extract data advanced search engine tools including text mining and ontologies were used. Ontologies allow incidents using words related to bolts to identify events. The search engine also allowed filtering of incidents based on parameters such as operator, equipment and failure mechanism.

A brief review (not a complete list) of commonly used standards related to bolts and bolted joints has been given (see Sec. 6). Most design standards for offshore equipment and structures specify requirements to bolts and bolted joints. Past experience has shown that there has been challenges regarding full traceability of bolt material origin and coating, and in some cases conflicting material requirements between standards. Over the last decade several standards have been issued with the objective of providing better bolt specification and improved practice for bolted joints (e.g. API 20E/F /19, 20/, ISO 1591-4 /16/, ASME PCC-1/24/). Some recommendations to improve the integrity of bolted joints are given in these standards.

In this report recommendations are given to improve the integrity of bolted connections by defining clearer requirements particularly:

- for assembly of bolted connections, and
- maintenance and integrity management

2 INTRODUCTION

2.1 Background

The Petroleum Safety Authority (PSA) has requested a project study to give an updated status regarding use of and incidents with bolts, and to give recommendations on potential development needs to reduce risks.

DNV GL has reviewed PSA's Incidents database ("Hendelsesdatabasen") and available Investigation reports ("Granskningsrapporter"). In addition, DNV GL's learnings from numerous failure investigations of bolted connections were utilised by DNV GL experts. In that respect, DNV GL has utilised and adapted a search engine with the objective to identify incidents associated with bolted joints in the Norwegian oil and gas industry, and to obtain trending regarding causes of these incidents.

Management of a bolted joint's integrity covers the whole life cycle:

- Design
- Materials selection
- Manufacturing
- Installation
- Operation

2.2 Scope of work

This report covers the following topics:

- A brief overview of applicable standards for the industry
- Reference to current best industry practice documents for bolt technology
- Identification of risks associated with use of bolts considering frequencies of bolt incidents and describe associated risk regarding Health, Safety or Environmental (HSE)
- A brief description of the search engine prepared based on ontology

2.3 Limitations

The study aims to cover bolts having a HSE risk with the potential for a major accident. It covers both bolts for submerged (excluding subsurface) service and those exposed to marine atmosphere and is limited to:

- Pressure containing/retaining static equipment (flanges)
- Structural connections including bolted joints on helidecks made of aluminum

Rotating equipment and BOP is not specifically covered by the study though the same guidance and requirements will also apply for such equipment. Additionally, seal technology (gaskets) is not addressed specifically.

2.4 Abbreviations and definitions

BSEE	Bureau of Safety and Environmental Enforcement
BOP	Blow out preventer
HC	Hydrocarbons
HE	Hydrogen embrittlement
HISC	Hydrogen induced stress cracking
JIP	Joint Industry Project
NCS	Norwegian continental shelf
NLP	Natural Language Processing
OCR	Optical Character Recognition
OREDA	Offshore & onshore reliability data
PSA	Petroleum Safety Authority Norway (Petroleumstilsynet)
RBI	Risk based inspection
HSE	Health, safety and environment

A fastener can be defined as a metallic screw, nut, bolt, or stud having external or internal threads /12/. In this report the word 'bolt' has been used as a general term.

A bolted joint can be defined as two parts clamped together using bolts transmitting loads between the parts. Flanged connections are the main applications for use of bolts both topside and subsea, both for pressure retaining equipment (i.e. not directly exposed to production/injection fluids) and for some application in loadbearing structures. Sealing of flanges also includes joint gaskets to ensure a leak tight connection. In this report the term 'bolted joint' has been used.

3 BASIS FOR WORK

The basis for the work has been:

- PSA's Incident database (”Hendelsesdatabase”) for the time period from 2000 to May 2018 /1/
- Investigation reports from PSA Ref. /2-6/ and /56-64/
- Review of international reports on bolted joints /7-11/
- Applicable standards and recommended practices for bolts and bolted joints /12-55/

The OREDA (or other international databases) on incidents was not reviewed, since OREDA is not open in the public domain. Strict regulations exist for accessing such data. These were not challenged by the study team and data from such databases was not included in the scope of this study.

The method applied for this study with digital search and retrieval of data from incident reports and data bases, requires data to be electronically readable. Old paper-based data are therefore difficult to include. There are techniques available for OCR conversion of such documents. Reviewing data from paper-based sources was not part of this study.

4 PREPARATION OF SEARCH ENGINE

The search engine combines search in structured data (PSA's incident database) with search performed by text mining for search words in pdf reports (PSA's investigation reports). The search engine offers a free-text search option together with controlled search by using defined keywords expected to be vital for the bolt study. The search engine concept is general in nature but has been tailor made for this bolt study report. The primary purpose of the search engine is to easily identify relevant information as a replacement of tedious manual searching and counting.

Key words are organized according to an ontology. The bolt failure ontology contains words, terms, synonyms and constraints between such elements defined by material specialists. The idea behind this concept is that knowledge about which terms that are related and used when constructing search, can be captured in the ontology by learning from specialists. Such knowledge can then be made available also for novice users. For the bolt study this functionality has only partly been implemented.

Key words selected to be included in this ontology were as listed in Table 4-1 below. An example of how these key-words appear and are used for navigating in the database is illustrated in Figure 4-2.

Table 4-1 Bolt study key-words included in the ontology

Utstyr ID - Norwegian	**Equipment ID - English**
Bolt	Bolt
	Fastener
Mutter	Nut
Nagle	Plug
	Stud
Flens	Flange
Gjenge	Thread
Hode	Head

Feilårsak ID - Norwegian	**Failure mechanism ID - English**
Korrosjon	Corrosion
Overbelastning	Overload
Utmatting	Fatigue
Tretthet	
Moment	Torque
Tiltrekking	Tightening
	Make-up
Hydrogen	Hydrogen
HISC	HISC
Sprekk(ing)	Cracking
Spenning	Stress
Forsprøing	Embrittlement
Vibrasjon	Vibration
Brudd	Fracture
Slitasje	Wear

Andre ord - Norwegian	**Other words - English**
Lekkasje	Leak
Ulykke	Accident
Skjær	Shear
Trykk	Compression
Intermetalliske fase	Intermetallic phase
Lav temperatur	Low temperature
Toleranse	Tolerances
Dimensjon	Dimension
Forspenning	Pre-tension

Belegg	Coating
Galvanisert	Galvanized
Smøring	Lubrication
Gjengetape	Thread tape
M (stor bokstav)	M (as capital letter)

The data from the incident reports (PSA's hendelsesdatabase) was made available as an Excel file with columns holding the various fields in the database and with one row for each record in the database. By filtering out the columns of interest for the bolt study, but by keeping all rows, a simple structured database was recreated from the Excel file. An example resulting from a free-text search from using the term 'bolt AND flens' as search words is shown in Figure 4-1.

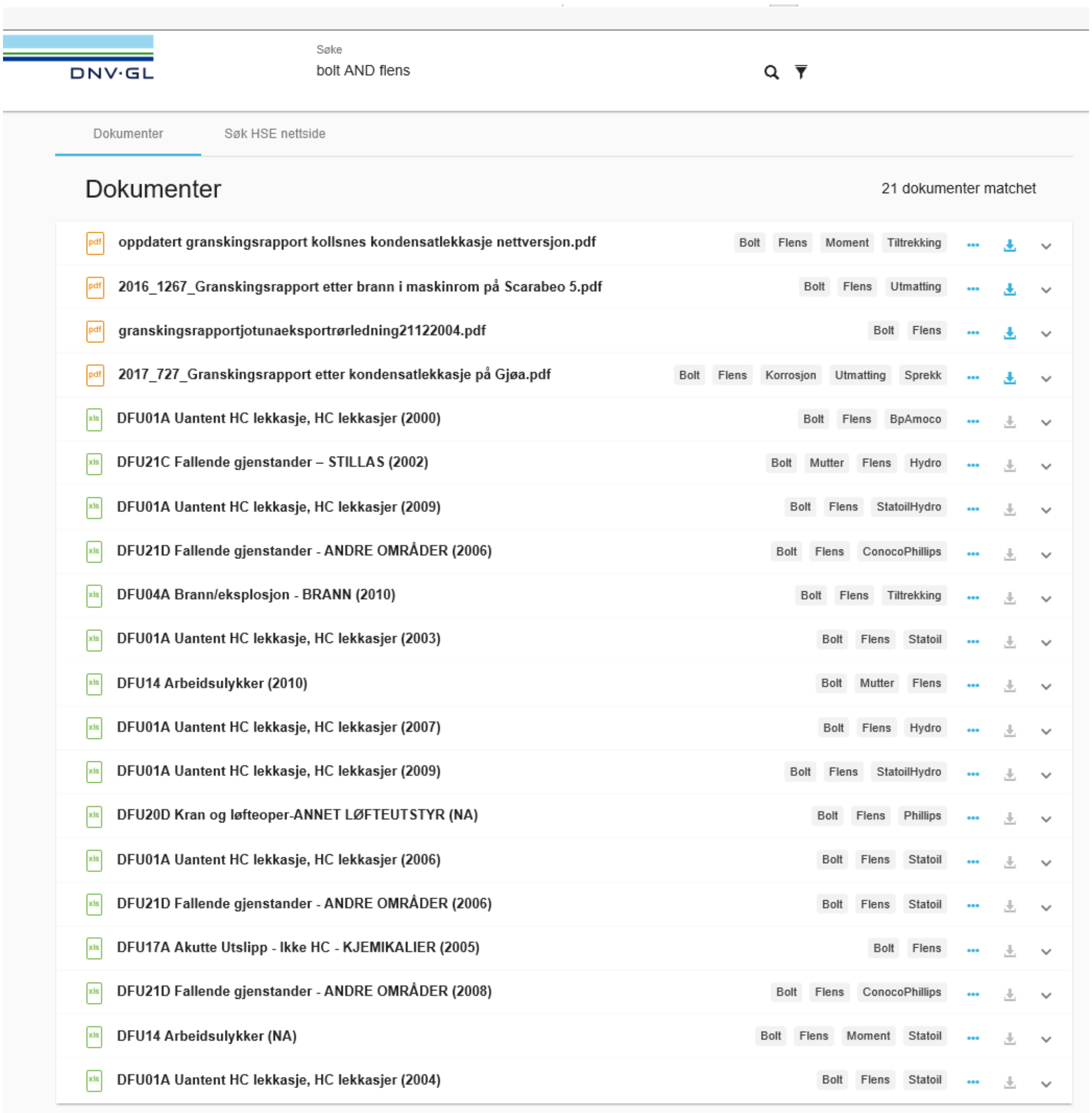


Figure 4-1 Result of a search by combining the keywords "Bolt" and "flens"

Both an English and a Norwegian version of the system was prepared. Switching between the languages are performed by a key click. Most of the documents and records found in the incident database and in the documents are in the Norwegian language. Some documents are in English.

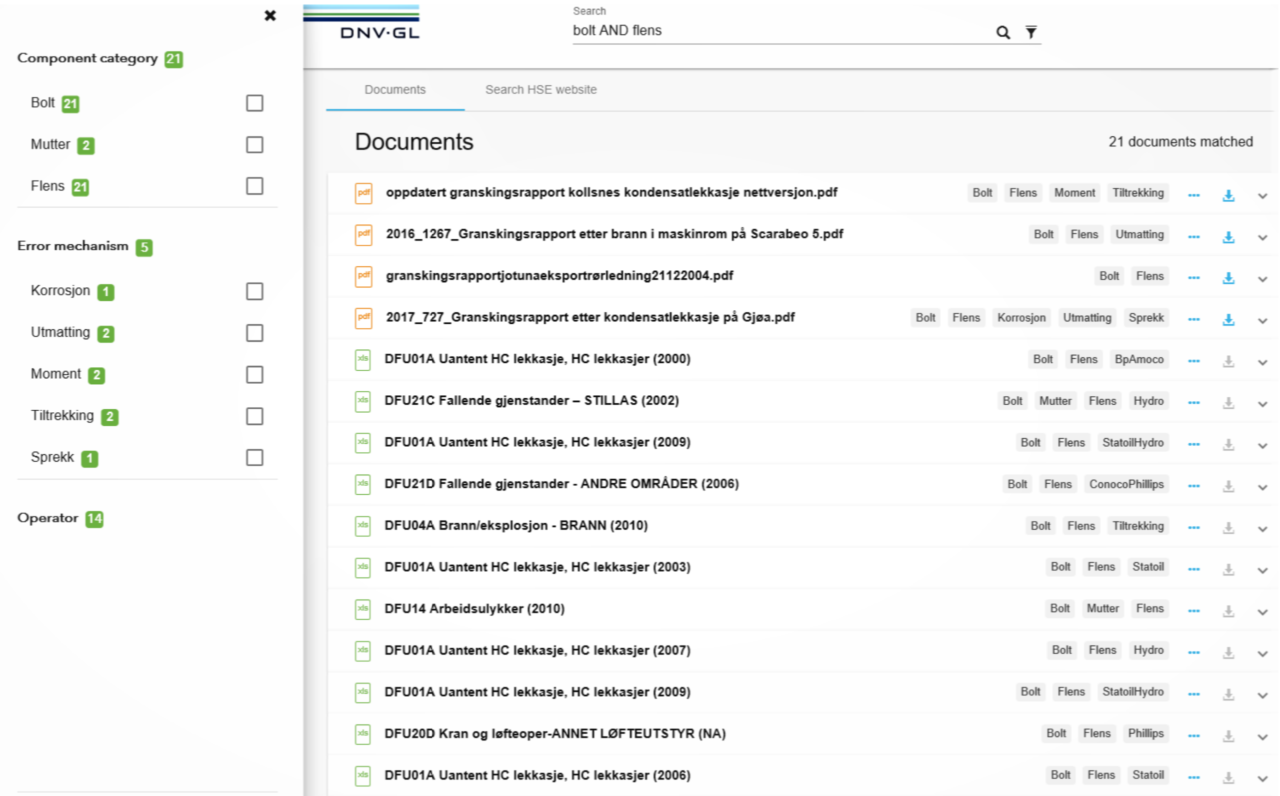


Figure 4-2 Ontology based search

By using the ontology, the search result from the free text search can be further narrowed. The number behind each term in the search menu identifies how many of the listed documents/excel rows that contain the specific search word.

By clicking on the name of the document or record identifier a summary of the document (or record in the PSA incident database) will be displayed.

By clicking on the "…" (three dots) symbol, "highlights" from the document or record are displayed.

By clicking the download icon, the complete document will be opened in e.g. a pdf-reader. If the record is from the database there is no document to download and nothing will happen.

A search in the HSE website (English public HSE database) is automatically triggered with the current search words. Current search words are those words that have generated the results currently being displayed.

The Bolt Search Engine is running on DNVGL's secure Veracity platform. This requires access to be granted by system administrators before first-time use.

The Bolt Search Engine can easily be adapted to search for other terms than bolt related as in this case. Additional documents (e.g. the complete library of incident reports) can be included. Document archives from external sources similarly.

The ontology made for this study is focused on bolt terms. It can be expanded to include other terms and be developed to remember often used search words. In a learning process terms that are related can be remembered by including them in the ontology. The same with synonyms.

The free text search mechanisms can be made more advanced by allowing building more complicated search terms. This can be done by including routines for REGEX (Regular expression operations) search with the code developed for the search engine. REGEX is a concept for specifying search strings in a standardized way. Such search strings can be decoded to search expressions by program codes available with most programming languages.

5 REVIEW OF DATA

5.1 Review of PSA's Incidents database

12,156 incidents have been reported in the PSA's Incidents database in the time period from January 2000 to May 2018 /1/. Appendix A shows an overview of the data which shall be reported in connection with an incident. The database has primarily predefined options for reporting and two descriptive options related to the incident – description ("beskrivelse") of the incident and consequence ("konsekvens") of the incident. In those two fields, information related to bolted joints can be found.

The number of records containing the word "Bolt" in the data base are 335 (of which 4 are 'granskningsrapporter'). Records containing the word "Flens" (Flange) is 170 (of which 6 are 'granskningsrapporter'), irrespective of severity category. Records containing both the word "Bolt" and "Flens" is 21 (of which 4 are 'granskningsrapporter'). The reported number of incidents mentioning bolt or flange, or containing both words, is thus approximately 3%.

Except for the conclusions from the investigation reports, some of the bolt incidents made reference to predefined failure modes, failure mechanisms and contributing factors assumed to be relevant. The distribution is as follows:

- Moment ('moment') 15 incidents
- Assembly ('tiltrekking') 10 incidents
- Corrosion ('korrosjon') 6 incidents
- Fatigue ('tretthet/utmatting') 4 incidents
- Crack ('sprekk') 3 incidents
- HISC 1 incident
- Overload ('overbelastning') 1 incident
- Tension ('spenning') 1 incident

Only one incident refers to suspected HISC of a screw in a subsea sensor flange.

It is obvious that very few records mention a specific failure mode or failure mechanism. Thus, it has not been possible to identifying any trends in the causes of bolt failure incidents. Most of the reported incidents in the database do not describe the root cause of failures but the potential hazard and the consequence of the incident. This has made it difficult to establish any clear trend regarding root causes of bolted joint failures.

Most incidents have been reported to be associated with:

- Dropped bolt or tool caused by vibration, inadequate design and inspection, inadequate procedures for bolt make-up, incorrect tightening (loss of tension, loose bolts)

Figure 5-3 illustrates the frequency of other words found in the database in conjunction with the word "bolt/bolter" (clustering). The size of the words illustrates the frequency of other words which can be associated with the word bolts ("bolter"). Words like "Area" ("området"), fell ("falt"), "dropped object" ("fallende gjenstand"), "came loose", ("løsnet"), "weight" ("vekt") are words which can be associated with the words "bolt/bolter". Loose and falling bolts appears to be the main cause and consequence that can be associated with bolts.

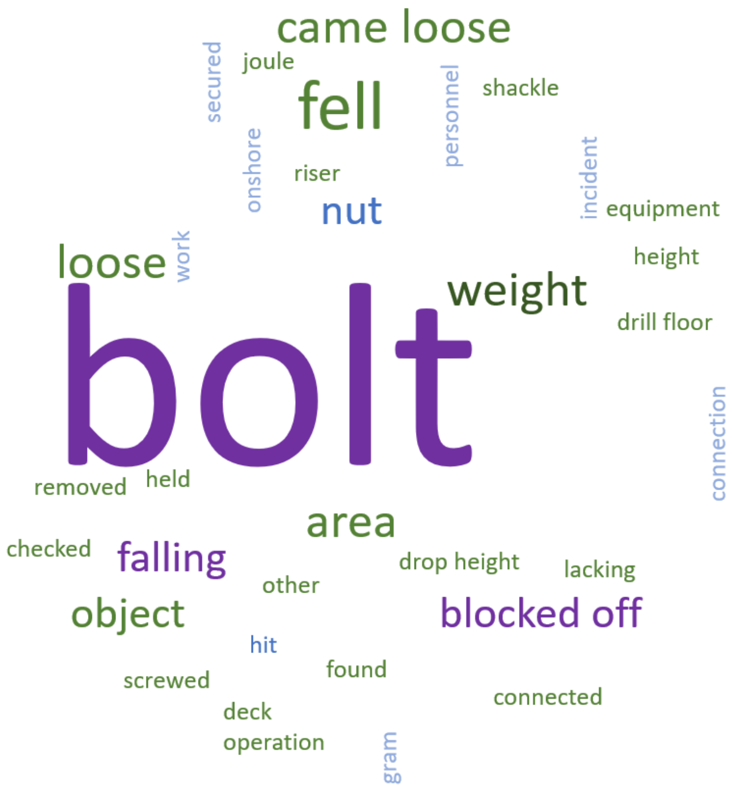


Figure 5-3 Clustering - Frequency of other words in conjunction with the word "bolt/bolter". Note that the words in the illustration have been translated to English as the majority of the words in the database were Norwegian.

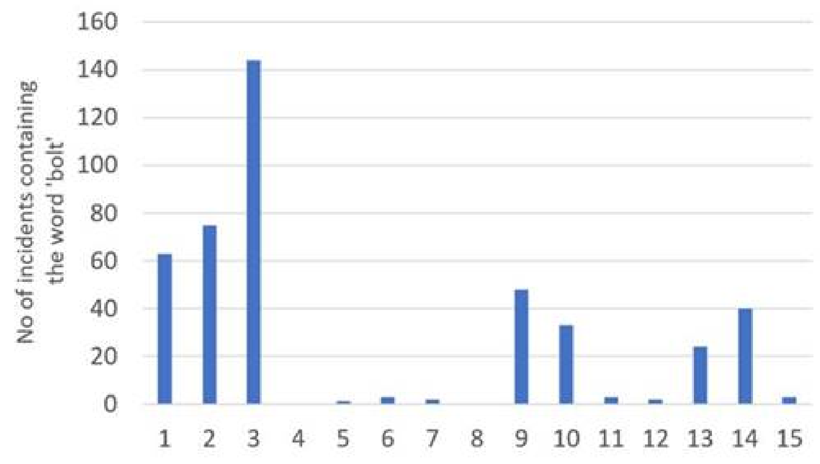
Word clustering is a NLP technique for partitioning sets of words into subsets of semantically similar words. In this study we investigated how word clustering techniques could be used to identify patterns in the incident databases and investigation reports frequently appearing together with the key word, as the word "bolter" in Figure 5-3. The font size gives a visual impression of the number of times the words have been found in this context while the colour just has been used for creating the visual image.

Figure 5-4 shows the distribution of incidents related to bolts per area description ("område_system") given in the database. Incidents related to bolts appear to be more frequent in areas for "drilling and well" ("bore og brønn") and "utility systems" ("hjelpe og støttesystemer").

A high number of incidents are registered towards unspecified areas as "Blank" ("no area reported") and "others" ("andre"); The actual consequences described for "Others" is mainly related work accidents & dropped objects. The actual consequences described for incidents reported as "blanks", is mainly related to dropped object, work accident, unignited hydrocarbon leaks and fire/explosion.

A higher frequency in the "drilling and well" area could be explained by a periodically higher human activity in this area than others.

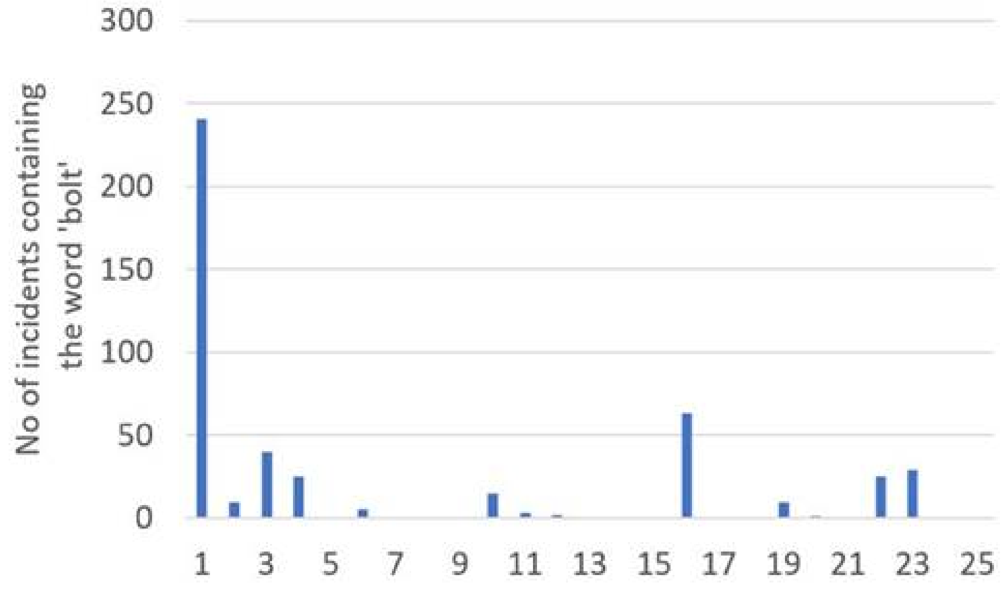
The high frequency for "utility systems" is more difficult to explain. Most inspection programs are based on risk assessments, where utility systems normally will obtain much lower risk than the main hydrocarbon systems. Consequently, they may be given less priority when planning for and selecting areas for inspection.



1	Blank- no information reported
2	Other
3	Drilling and well
4	Fire and gas system
5	Diving
6	Electrical installation
7	Subsea production system
8	Helicopter transport
9	Utility system
10	Main process
11	Living quarter
12	Compression
13	Construction and maritime system
14	Lifting operation
15	Pipeline system

Figure 5-4 Distribution of incidents related to bolts per area description

Figure 5-5 shows the distribution of consequence categories. Dropped objects and work accidents are the dominating consequence categories, while un-ignited hydrocarbon incidents, crane related incidents and “other” are also frequently registered.



1	Dropped object	14	Helicopter incident
2	Well	15	Man overboard
3	Unignated hydrocarbons	16	Work accident
4	Crane	17	Illness - work related
5	Ignated hydrocarons	18	Electricity failure
6	Fire	19	Acute hydrocarbon discharge
7	Ship in collision course	20	Diver
8	Driving object	21	Hydrogen sulphide (H_2S)
9	Collison with service vessel	22	Crane
10	Damage to the construction	23	Other
11	Leakage under water	24	Illness - not work related
12	Damage to subsea production system	25	Blank – no information
13	Evacuation		

Figure 5-5 Number of incidents related to bolts per consequence category

5.2 Other sources of failure data

DNVGL has created a database with all failure investigation reports published by DNVGL between 2008 and 2018. The data shows that fracture of bolts is a quite common failure mode. The causes of these failures have mainly been identified as fatigue, brittle fracture, overload or HISC.

Overload, tightening and torque appears to be recurring contributing factors related to these types of failures. This is typically associated with inadequate procedures or lack of technician training for the assembly of bolted joints.

HISC is also a frequent failure mode for bolts. Particularly for carbon steels with high strength/hardness, Alloy 625 and Alloy 718. The reason behind this is not conclusive and should be further examined.

Review of selected subsea bolt failures between 2002 and 2013 (for bolts exposed to CP) given in Ref. /8, 9, 11/ concluded that the causes of bolt failures were related to:

- Hydrogen embrittlement caused by a too high material hardness.
- Inadequate heat treatment of raw material causing hydrogen assisted cracking.
- Inconsistent requirements between standards (e.g. hardness).
- Design standards do not address material requirements specifically.
- Inadequate procedure for baking of zinc coated bolts causing hydrogen assisted cracking.
- Quality control system did not disclose shortcoming in the sub-contractor's manufacturing procedures.

The reports in Ref. /8, 9, 11/ concluded that the industry need to develop a consistent set of standards, including requirements that allow for tracking bolted joints during their service life and an improved management standard addressing subcontracts related to manufacturing and mechanical integrity. A standardized laboratory test for bolt materials (with and without coating) susceptibility to HE should be developed.

The National Academy of Engineering /8/ held a workshop in 2017 with the objective to develop a comprehensive awareness of the outstanding issues and development needs associated with bolt material failures in the Offshore Oil and Natural Gas Operations. Key issues discussed at the workshops included material, design loads, preload, coating, cathodic protection, failures, operation and quality. The conclusions from the workshops were not clear, but the following were highlighted as important issues to work further with:

- Hydrogen embrittlement appeared to be one area that needs more attention (including procedures associated with metallisation of bolts/galvanising).
- The industry and standardisation bodies must create/require tighter material and manufacturing specifications and better quality control activities for bolts.
- Engineers should reduce their reliance on testing alone.
- Creating tests that better measure fitness-for-service.
- Improve failure reporting, analysis, and sharing of results.
- The industry should be better at learning from failures (and near misses). This could be done by adopting the principles from the nuclear industry, commercial aviation, and NASA. These organizations are highly reliable because of the way they value learning from failures.

It was further pointed out that the quality management system specified in API Q1 /44/, for requirements to manufacturing for the petroleum and natural gas industry, is more stringent than ISO 9001 /45/. NORSOK M-630 /14/ requires that the manufacturer shall have a qualified system in accordance with ISO 9001.

Both refence /9/ and /8/ highlight hydrogen embrittlement as an area that needs more attention. Only one incident referring to suspected HISC of a screw in a subsea sensor flange was found in the "hendeslesdatabasen". HISC of bolts has been a major issue on the NCS but this is not captured by the entries in the 'hendelsdatabasen'. Probably because they have occurred subsea and had more commercial than safety related implications. As described in the report from the National Academy of Science in the US /11/ there have been registered safety critical incidents involving HISC of bolts.

6 REVIEW OF STANDARDS AND BEST PRACTICE FOR BOLTS / BOLTED JOINTS

6.1 General

This section gives general but not complete, overview of relevant standards for:

- Materials selection of bolts for bolted joints.
- Relevant manufacturing standards and relevant quality control requirements to the end product.
- Best industry practice for installation of bolted joints.
- Guidance for bolted joints in aluminium structures is also given.

It is not the intention to list all standards related to bolted joints. Most of the referred standards refer further to other standards also applicable for design and manufacturing of bolts and bolted joints.

Requirements for bolts is defined in the applicable design standard. These standards refer to manufacturing standards for bolts and may also have some additional requirements related to quality control activates during manufacturing, as well as material properties. In addition to this, project specific or company specific requirements may also apply.

Standards covering bolted joints and flanges contains normally guidance (informative) on how to make-up such connections.

6.2 Standards for material selection and manufacturing of bolts

Materials and coating selection of bolts is mainly based on mechanical properties, strength, toughness, resistance to hydrogen embrittlement (HE) and corrosion. The most commonly used standards for low alloy bolting is ASTM A193/A193M /48/, ASTM A194/A194M /49/ and ASTM A320/A320M /50/. The bolts exposed to marine atmosphere is normally galvanised, whilst subsea bolts do not require galvanising. Corrosion resistant alloy recommended for bolting when exposed to marine atmosphere is 25 Cr duplex stainless steel /14/. Corrosion resistant alloys for submerged service are typically; Alloy 718 (API 6ACRA /31/), Alloy 625, Alloy 686. Alloy 625 can be used without cathodic protection whilst the others require cathodic protection /12, 15/. Compliance to ISO 15156 may be relevant for certain environments. A more complete list of recommended bolt specifications is given in e.g. NORSOK M-001 /12/.

A new API standard (Technical report 21TR1 - pending final approval) /51/ under preparation, covers guidance for the materials selection and the manufacturing process for low alloy steel, nickel-based alloys and stainless steel. It gives a good overview regarding considerations to be made when selecting bolts and covers the following topics:

- Impact of the environmental condition
- Bolting threats and barriers to mitigate the threats
- The manufacturing process which may affect the final properties of the bolting

The standard does not specify application limits for different bolt materials. Application limits can, however, be found in other standards such as NORSOK M-001 /12/, API 6A /17/ etc.

Experience from failures has shown the importance of using qualified manufacturers and to have traceability of the origin of the bolt material and the coating. The issue of API 20E /19/ and API 20F /20/, covering low alloy and carbon steel bolting, and corrosion resistant alloys, respectively, were issued in order to improve the manufacturing process of bolts. These API standards specify requirements for qualification, production and documentation and shall now apply when referenced by an applicable API equipment standard or otherwise specifically specified.

Further API Standard 6ACRA gives requirements for age hardened nickel-based alloys as a supplement to API 6A. Other standards referred to is ISO 898 /37/ and ISO 3506 /36/, covering mechanical properties of carbon steel and low alloy steel, and corrosion resistant bolts, screws and studs, respectively.

A DNV JIP from 2008, aimed to give guidance on the management of bolt integrity and bolted joints (mostly extracted from existing standards). The JIP concluded, among other things, that bolts should have full traceability of all documentation and certificates throughout the manufacturing stage, and unambiguous marking. It is also recommended that the supply chain is kept short and transparent. It suggests the end user to develop a 'Fastener Data Sheet' as part of the bolt specification which clearly defines the requirements to all relevant aspects of the end product. Currently there is no standard that has fully adopted this as standard documentation.

Bolted joints in aluminium structures is known to be a challenge due to the risk for crevice corrosion and galvanic corrosion between the bolt material (being typically stainless steel or galvanised bolt for marine atmosphere and submerged condition, respectively) and the aluminium /41/. Use of coating, sealing the overlapping area is one option to mitigate this. Electrical insulation of the bolt from the aluminium has also been used to mitigate corrosion. Cathodic protection will balance the electrochemical potential of the bolted joint, mitigating galvanic corrosion. However, the risk for crevices' corrosion should be assessed on an individual basis considering the actual joint design.

Recommendations for bolted joints of aluminium is given in the following standards:

- EN 1090-3 /42/: Execution of steel structures and aluminium structures, gives some requirements regarding bolting and sealing of crevices
- EN 1999-1 /43/: Eurocode 9 Design of aluminium structures, Annex D, gives recommendations related to corrosion protection
- Norsok M-001 /12/: Recommendations regarding bolt materials and compatibility between aluminium and different materials for topside applications

Bolts and nuts shall normally be supplied with a material certificate to EN 10204 Type 3.1 /55/.

Improvements opportunities

Based on the review the following improvement opportunities are identified:

- Development of a standard or best practice, describing all relevant requirements for manufacturing, testing, quality control activities and certification according to the deployed design standard to ease procurement and to avoid inconsistency in requirements between different standards (see also Sec. 5.2).
- NORSOK M-001 specifies specific bolt grades to be used (including requirements to manufacturing, testing etc. in NOROSK M-630). This may exclude use of other bolt materials. A regime for how to evaluate and qualify new material grades for specific applications should be developed.

6.3 Design standards and their requirements to bolts and bolted joints

Bolted joints in the offshore industry are specified in a range of standards. Some of the most relevant standards covering design of bolted joints and selection of bolts are given in Table 6-1. The list is not complete, as these standards also make cross-references to other normative standards relevant for design and installation of bolted joints, and standards for manufacturing of flanges and bolts.

Table 6-1 Some standards covering the design of bolted joints.
(The referenced standards are listed Sec. 8)

Standard	Equipment	Comment
PIPING AND PROCESS EQUIPMENT:		
ASME B31.3	Process piping 1)	Design of process piping. Reference to applicable bolting specifications given. Gives general requirements for assembly of bolted joints. Flanged joint assembly, refence is given to ASME PCC-1, BPV Code and non-mandatory guidance in Appendix S. Also applicable for subsea manifold piping.
ASME B16.5	Pipe Flanges and Flanged Fittings 2) Piping system	Design of flanges. Lists applicable ASTM specification of bolts and material specifications for flanges. Gives recommendations on flange bolting, gaskets and jointing in general.
EN-1591-1	Flanges and their joints 2) Piping system	General standard. Gives flange and bolt pretension calculation method for bolted gasketed circular flange joints and specified to be useful for joints where the bolt load is monitored during bolting up.
NORSOK L-005	Compact flanged connections for joining of equipment, valves, piping, piping components	Gives requirements for design and manufacturing of materials. Refers to international codes such as ASME B16.5/B31.3 etc. as normative standards for flanged joints and bolts.
NORSOK L-001	Piping and valves	Gives reference to standards for dimension of flange and bolting (ASME), and material requirements for flange and bolts (ASTM and NORSOK M-630).
EN 1092-1:2001	Flanges and their joints Piping system and valves	Design and manufacturing of circular steel flanges Requirements for bolts refers to EN 1515-4.
SUBSEA EQUIPMENT, PIPELINES, DRILLING AND WELL		
API 6A (ISO 10423)	Wellhead and Christmas tree equipment	Design standard. Gives requirements for bolting materials, dimensions, utilisation of bolts, bolt torque etc. including required testing and documentation of bolt materials. Gives guideline for calculating stud bolt lengths for 6B and 6BX flanges and flange bolt torque
API 17D / ISO 13628-4	Wellhead and Christmas tree equipment	Design standard. Covers design methods and ring gaskets. Specifies requirements to closure bolting; dimensional tolerances and bolt length for different flange sizes and pressure ratings; allowable stress and hardness and compliance with ISO 15156 where relevant. Refers to international codes such as ASME B31.8/B31.3/ISO 10423 etc. as normative standards for flanged joints and bolts Assembly guidelines of ISO (API) bolted flanged connections is given in Annex G.

Standard	Equipment	Comment
ISO 13628-15 / API 14D	Subsea structures and manifolds	Provides general design and manufacturing requirements for compact flange connections used for joining equipment, valves, piping and other piping components. Specifies limitation to SMYS and hardness, refers to ISO 13628-1 for materials limitations of bolts.
DNVGL-ST-F101	Pipeline components and assemblies	Referenced standards for bolts and bolted joints are ASME VIII Division 2/EN 13445/PD 5500 Flanges: ISO 15590-3/ISO 7005-1 or NORSOK L-005/EN 1591-1/API
API 16A	Drilling equipment	Refers to API 20E and 20F for pressure containing, retaining, closure and utility bolting
LOAD BEARING STRUCTURES		
NORSOK N-004	Steel structures 3)	Covers design of steel structures including design factors for bolted joints. Gives reference to other international standards for bolted structural joints such as e.g. EN 1993-1-8 /69/.
ISO 19902	Fixed steel structures	Design standard. Gives guidance on bolt mechanical properties, fatigue consideration etc. and design of connections.
ISO 19901-3	Top-side structures	Design standard, fabrication and installation. Gives guidance on bolted joints. For bolting materials reference is given to ISO 3506.
DNVGL-RP-C203	Design of offshore steel structure	Widely used recommended practice (informative) for fatigue design of structures including bolted joints and flanges. Includes bolted joints. Considers bolts in both tension and shear. Covers steel bolts exposed to air for grades up to 10.9 and stainless steel bolts.

1) Ref. also ASME B16.50 and ASME B16.20 - Metallic gaskets for Pipe flanges

2) Ref. also EN-1591-2/3/5 Flanges and their joints – design rules gasketed circular flange connections

3) It should be noted that prior to revision 3 of NORSOK N-004 (2013), NS 3472 /68/ was referred as the normative design standard for offshore steel structures. NS 3472 was withdrawn in 2010 and replaced with NS-EN 1993-1-8 /69/, which is now the normative reference for design of joints in offshore steel structures in NORSOK N-004.

6.4 «Best industry practice» for installation and maintenance of bolted joints

Design codes for pressurised bolted joints, such as EN 1591-1, require controlled bolt tightening. This implies that procedures need to be in place to control the bolt torque considering the use of lubrication/coating or not. Moreover, the competence of the bolting technicians will also be a key factor in order to ensure correct make-up. The need for qualification and training of technicians is therefore very important. Relevant guidelines for assembly of flanged joints including standards for competence and qualification of personnel/technicians is given in Table 6-2.

Table 6-2 Guidelines for managing integrity of bolted joints and for training. (The referenced standards are listed Sec. 8)

Standard	Description	Comment
ASME PCC-1	Guideline for pressure boundary bolted flange joint assembly	Appendix A gives recommendations for qualification of technician
EN-1591-4	Qualification of personnel competency in the assembly of the bolted joints of critical service pressurized systems	Qualification regime for assembly. Certification to this European Standard does not represent an authorisation to operate, since this remains the responsibility of the employer, and the certified person may require additional specialised knowledge of employer-specific procedures, processes and equipment.
Oil and Gas UK (Energy institute)	Guidelines for the management of integrity of bolted joints for pressurised systems	Gives guidance on bolting technology and practice, training, management of leaks and inspections. Example on tagging of joints and how to keep life cycle information of a joint.
NOG Handbook Guideline 118	Guideline in flange work.	Handbook in bolted joint. Used as basis for training.
API 17D / ISO 13628-4	Design and operation of subsea production systems – subsea wellhead and tree equipment	Annex G gives assembly guideline and example on a make-up record for a joint
NORSOK N-004	Steel structures	Norsok N-004 and the normative reference EN1993-1-8 provides neither normative requirements nor recommendations related to the assembly process and to in-service inspection and follow-up.

According to the referred standards, manufacturer shall document make-up torque/tension as part of the end connection. Recommendations of such a record can be found in the standards. Moreover, it is recommended to have a short assembly record to uniquely identify each joint permanently, fixed to the joint or similar identification system with the purpose to:

- Facilitate joint assembly quality control
- Provide a record of the joint assembly
- Record joint history

The standards listed in Table 6-2 provide primarily guidance on how to manage bolted joints integrity (i.e. not mandatory requirements). It is therefore the end user responsibility to prepare a system for handling bolted joints in terms of preparation of procedures, to ensure adequate training of the technicians and to have a traceable system in place for handling the integrity of bolted joints during service. This may include, routines for checking for corrosion of bolts and maintenance of bolt tightening. Ref. /10/ gives guidance to the in service inspection of bolted joints, including inspection techniques and mitigating measures.

Guidelines used for the preparation of risk-based inspection programs (e.g. DNVGL-RP-G101 /46/, ASME PCC-3 /47/) do not specifically address bolts and bolted joints. For systems where the reliability of a bolted joint is crucial for the integrity of the system, these joints should be treated in the same way as other equipment in the analysis.

Improvement opportunities

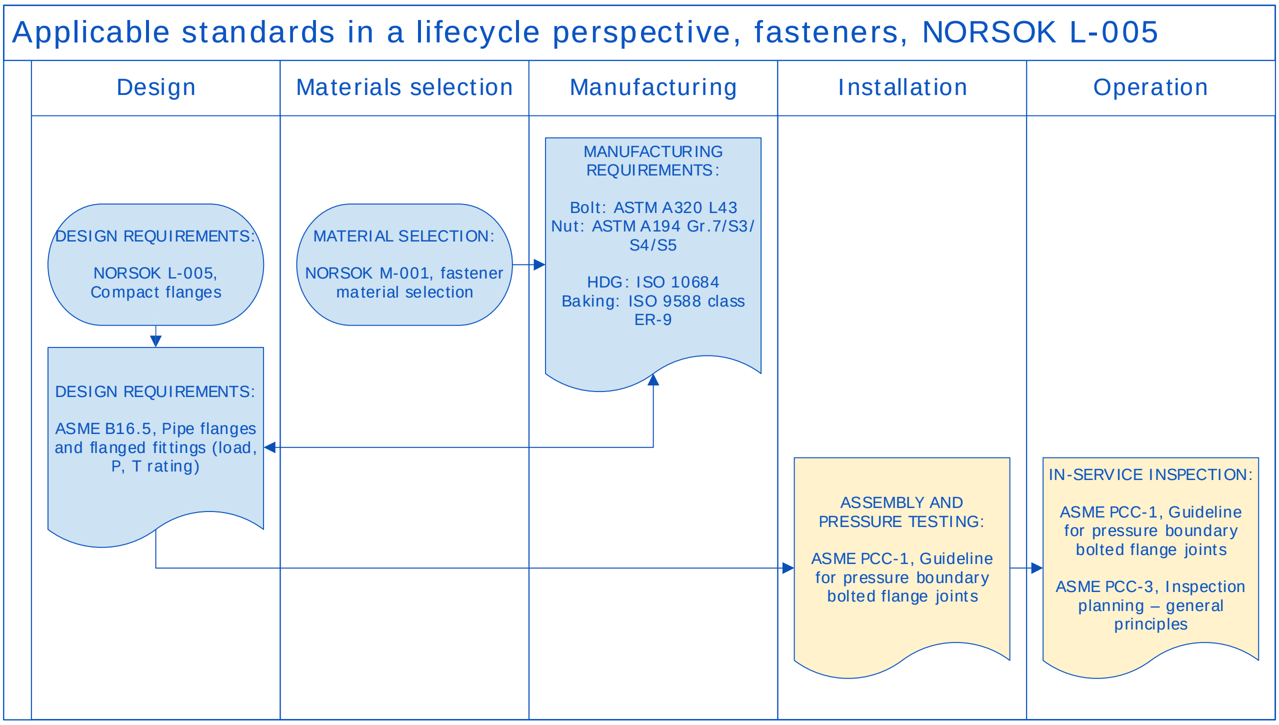
Based on the review the following improvement opportunities are identified:

- Since requirement to the make-up process of bolted joints are generally given as guidance ('informative') in the standards, a common standard for the make-up process of bolted joints would be beneficial. This should also include qualification and competence requirements to personnel/technicians (ref. EN-1591-4).
- Guidelines for the preparation of risk-based inspection programs (e.g. DNVGL-RP-G101 /46/, ASME PCC-3 /47/) should further be developed to cover bolted joints. Moreover, development of an assembly record to uniquely identify each joint history (facilitate joint assembly quality control, history, inspection and maintenance related to loss of pre-tension (e.g. loose bolts/nuts) and degradation (e.g. corroded bolts/nuts)) should be part of the operational documentation.

6.5 Lifecycle application of standards - Example

Section 6.1 to 6.4 in this report outline standards relevant to bolts and bolted joints in different phases of an asset's lifetime, i.e. design, material selection, manufacturing, installation and operation. In this section, an example is presented to show the applicability of the referred standards through the lifetime of one bolted joint that will be exposed to marine atmosphere. The selected case is a compact bolted flange in accordance with NORSOK L-005 /13/.

Referred standards often have a number of normative and informative references, where the normative standards are mandatory, and the informative standards are none mandatory. The purpose of this example is to show what is considered to be normative standards and "best practice" selection of references among the alternatives presented in the relevant standards. The example is illustrated in Figure 6-1.



Legend:

Mandatory / Normative standard

Guideline / Informative standard

Figure 6-1 Example; standards applicable for fasteners in compact flanges in accordance with NORSOK L-005 and material selection in accordance with NORSOK M-001, in a lifecycle perspective.

NORSOK L-005 gives some normative (mandatory) requirements for the design phase and describes that e.g. ASME B16.5 /54/ shall apply. EN 1591-1 /53/, describes design rules and calculation method for gasketed circular flange connections and is an example of an informative standard referenced in NORSOK L-005, which has not been selected for this case.

NORSOK L-005 gives general guidance related to material selection but is not specific on which materials to use for specific environments. NORSOK M-001 /12/ is not referenced in NORSOK L-005 but is considered a best practice reference for material selection of fasteners for use in a marine environment. For this case a stainless-steel flange (e.g. ASTM A182 F316L) and hot dipped galvanized (HDG) low alloy steel fasteners, ASTM A320 L43 /50/ bolt and ASTM A194 /49/ nut is selected. NORSOK M-001 refers to ISO 10684 /65/ and ISO 9588 /66/ for HDG and baking, respectively. ASTM A153 /67/ is an alternative reference for HDG but the equivalent ISO standards are typically selected where possible.

According to NORSOK L-005, the supplier shall provide a maintenance procedure for the compact flange, but specific maintenance requirements are not provided. ASME B16.5 specifies that the assembly of the flange and bolt tightening shall be according to a proven procedure and refers to ASME PCC-1 /24/ as a mandatory reference for flange assembly. However, ASME PCC-1 is a guideline and provides only a set of recommendations regarding development of assembly procedures and training of personnel and no specific requirements. ASME PCC-1 may therefore be considered as a 'best practice' for the assembly process and not a specification.

Concerning the operational phase, there are limited specific requirements related to bolted joint. ASME PCC-1 gives guidance on troubleshooting in case of leak incidents. ASME PCC-3 /47/ gives general guidance on how to develop and implement a risk base inspection program but there is no specific methodology for how to implement a system for management of bolted joints during the operational phase. Hence, there is need for development of a risk-based approach (scheme) for inspection and maintenance of bolts and bolted joints during the operation phase.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Findings based on the PSA incident reporting

The PSA database has been reviewed with the objective of identifying incidents associated with bolts and bolted joints that may constitute a major SHE risk. The data has main focus on the hazard and consequence of the incidents; e.g. injury to employees, experienced leaks etc. The main observations made are:

- The bolt failures were frequently linked to dropped object incidents which seem the most frequent consequence related to bolts. Particularly related to “drilling and well” area.
- Among the incidents classified as “serious” (“Alvorlig”) and “with high potential” (“Stort potensial”), incidents that can be associated with bolts appears not to be the main cause.
- 331 incidents related to bolts where identified in the database, which is approximately 3% of the reported incidents (12 156 total)
- Since the reported incidents do not necessarily conclude on the root cause of the failure, it has not been possible to see any trend related to frequency of different failure mechanisms.

7.2 Brief summary of standards for bolts and bolting joints

Most design standards for offshore equipment and structures specify requirements to or suitable bolts for bolted joints. This includes bolt grade/property class, design of bolted joints, applicable manufacturing standards for bolts, gaskets and flanges.

Past experience has shown that there have been challenges regarding full traceability of bolt material origin and coating, and in some cases conflicting material requirement between standards. Over the last decade several standards have been issued with the objective of providing better bolt specification and improved practice for bolted joints (e.g. API 20E/F /19, 20/, ISO 1591-4 /16/, ASME PCC-1/24/).

Generally, it appears that the standards primarily provide guidance on how to make-up joints rather than giving mandatory requirements. The same applies to integrity management of bolted joint during service (i.e. inspection and maintenance).

7.3 Recommendations and improvement opportunities

The following recommendation can be made to improve the information in the PSA database:

- The database should be extended to include the root cause of a failure (technical, operational and / or organisational) enabling learning from failures (e.g. link to relevant investigation report and a summary of the causes of the failure). This can be done effectively by including additional investigation reports in the database in addition to the entries in 'hendelsesdatabasen'.

The following improvement opportunities are recommended regarding standards and guidelines:

- Practice for integrity management of bolted joints is generally given as recommendations in the referenced standards. The recommendations should be reviewed to see if some requirements should be formalised.
- NORSOK M-001/M-630 specifies specific bolt grades to be used. This may exclude use of other bolt materials. A regime for how to qualify new material grades should be developed.
- Guidelines for inspection planning (i.e. RBI planning) does not address bolted joints specifically. Bolted joints should also be part of the RBI planning. This should also include a record to uniquely identify each joint history (facilitate joint assembly quality control, history, inspection and maintenance related to loss of pre-tension (e.g. loose bolts/nuts) and degradation (e.g. corroded bolts/nuts).
- Development of a "Fastener data sheet" to ease purchasing, describing all relevant requirements according to the deployed design standard and selected bolt standard to ensure that all quality control activities, test requirements and inspection certificates is clearly defined.
- It is recommended to define clearer requirements particularly:
  - for assembly of bolted connections, and
  - maintenance and integrity management

The following recommendations can be given from other public sources:

- Publicly available reports /8, 10/ have addressed risk for hydrogen embrittlement (HE) as an area that needs more attention, regarding e.g. standardised testing.

This study has not mapped ongoing initiatives related to improving knowledge and standards / requirements related to fasteners and bolted joints. It should, however, be mentioned that the American Petroleum Institute (API) has initiated a test program where the objective is "*(…) to improve fatigue assessments of critical bolted connections particularly in subsea applications by generating new test data*" /70/.

This study has not mapped or evaluated requirements related to qualification / performance assurance of bolted joints. Reference is made to welding / welded joints, where standardisation related to qualification is well established and implemented by the industry. Whether equivalent standardisation should be considered for bolted joints should be studied in future work.

8 REFERENCES

The latest revision of the listed standards applies.

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/11/ High-Performance Bolting Technology for Offshore Oil and Natural Gas Operations, DC: The National Academies Press, Washington DC, https://doi.org/10.17226/25032.

/12/ NORSOK M-001, Materials selection

/13/ NORSOK L-005, Compact flange connection

/14/ NORSOK M-630, Material data sheets and element data sheets for piping

/15/ ISO 21457, Petroleum, petrochemical and natural gas industries - Materials selection and corrosion control for oil and gas production systems

/16/ EN 1591-4, Flanges and their joints – Part 4: Qualification of personnel competency in the assembly of bolted connections of critical service pressurized systems

/17/ API 6A, Specification for wellhead and Christmas tree equipment

/18/ ISO 13628-1, Petroleum and natural gas industries — Design and operation of subsea production systems — Part 1: General requirements and recommendations

/19/ API 20E, Alloy and carbon steel bolting in the petroleum and natural gas industries

/20/ API 20F, Corrosion resistant bolting for use in the petroleum and natural gas industries

/21/ DNVGL-ST- F101, Submarine pipeline system

/22/ NS-EN 1592-4:2013, Flanges and their joints; Part 4: Qualification of personnel competency in the assembly of the bolted connections of critical service pressurised systems

/23/ ASME B31.3, Process piping

/24/ ASME PCC-1-2013, Guideline for pressure boundary bolted flange joint assembly

/25/ ISO 13628-15 Petroleum and natural gas industries – design and operation of subsea production systems – Part 15: Subsea structures and manifolds

/26/ Not in use

/27/ API 17D, Design and operation of subsea production systems – well head and tree equipment

/28/ NOG, Norsk olje og gass, Håndbok i flensearbeid, Rev. 05, 2017 (OLF Guideline 118)

/29/ ISO 19902, Petroleum and natural gas industries — Fixed steel offshore structures 2007

/30/ ISO 19901-3, Petroleum and natural gas industries – Specification requirements for offshore – Part 3: Topside structures

/31/ API standard 6ACRA, Age hardening nickel-based alloys for oil and gas drilling and production equipment (replace API specification 6A718)

/32/ DNVGL-RP-C203, Fatigue design of offshore steel structures

/33/ ISO 13628-4 Petroleum and natural gas industries – design and operation of subsea production systems – Part 4: Subsea wellhead and tree equipment

/34/ ISO -15156/all parts, Petroleum and natural gas industries – materials for use in H2S containing environments in oil and gas production

/35/ ASME B16.20, Metallic Gaskets for Pipe Flanges

/36/ ISO 3506, Mechanical properties of corrosion resistant steel fasteners

/37/ ISO 898, Mechanical properties of fasteners made of carbon steel and alloy steel

/38/ ISO EN 1092-1, Flanges and their joints – Circular flanges for pipes valves fittings and accessories, PN designated – Part 1: steel flanges

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/44/ API Q1, Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry

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/49/ ASTM A194, Standard Specification for Carbon Steel, Alloy Steel, and Stainless Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both

/50/ ASTM A320, Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service

/51/ API Technical report 21TR1, Materials selection of bolting – pending approval

/52/ ASME B16.50, Wrought Copper and Copper Alloy Braze-Joint Pressure Fittings

/53/ EN-1591-1/3/5, Flanges and their joints, Part 2: Gasket parameters, Part 3: Calculation method for metal to metal contact type flanged joint; Part 5: Calculation method for full face gasketed joints

/54/ ASME 16.5, Pipe Flanges and Flanged Fittings: NPS 1/2 through NPS 24 Metric/Inch Standard

/55/ ISO 10204, Metallic products - Types of inspection documents

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/66/ ISO 9588, Metallic and other inorganic coatings — Post-coating treatments of iron or steel to reduce the risk of hydrogen embrittlement

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/69/ NS-EN 1993-1-8, Eurocode 3: Design of steel structures – Part 1-8: Design of joints.

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APPENDIX A
PSA database report format

Table A-1 shows the report format for the PSA database.

Table A-1 Reporting format in the PSA database.

Incident report records	Description
id	Serial number
tidspunkt	Time of event/reporting
innretning_kode	Asset identifiaction number
innretning_tekst	Asset name
innretning_type	Type of asset (e.g. fixed platform, floater etc.)
felt	Asset name
operator	Operator
operator_kode	Operator identifaction number
saksaar	Year
saksnr	Casenummer
doknr	Document number
beskrivelse	**Description of the incident**
konsekvens	**Consequence of the indicidence**
tiltak_operator	Operators action due to the incident
tiltak_PSA	PSA action (Yes or No)
Erfaring	Experenivce (Yes or No)
politi_bistand	Assistance Police ((Yes or No)
beredskapsorg_aktivert	Emergence preparedness activity (Yes or no)
stans_boring	Stop drilling (Yes or No)
stans_produksjon	Stop production (Yes or No)
monstring_livbaat	Lifeboat (Yes or No)
granskningsrapport	Investigation reporting (Yes or No)
PSA_gransker	Investigation by PSA (Yes or No)
meldingstype	**Type of reporting (Predefined options)**
omraade_system	**Area or system (Predefined options)**
alvorlighetsgrad	**Incident severeity (Predefined options)**
faktisk_konsekvens	Consequence (Predefined options)
potensiell_konsekvens	Conseqence (Predefined options)
Tittel	Title on inscidence
kval_beskrivelse	Quality description (Predifined options)
kval_analyse	Quality Analysis (Predifined options)
kval_feilaarsaker	Quality root cause (Predefined options)

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