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ORIGINAL RESEARCH

Safety and reliability improvement of valves and actuators in the offshore oil and gas industry

Karan Sotoodeh[1] · **Ove Tobias Gudmestad**[1]

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Abstract

Valve failure is a major risk and a costly phenomenon in the offshore sector of the oil and gas industry. It results in severe negative consequences, such as a loss of assets, a loss of production due to plant shutdowns, and health, safety, and environmental (HSE) issues, such as hydrocarbon (oil and gas) spillage. Improving the safety and reliability of the valves and connected actuators is necessary to limit the occurrence of failure. This paper focuses on three aspects of improving valve and actuator reliability: material selection, design optimization, and boosting the safety integrity level (SIL). The first and second aspects are applicable only to valves, but the third targets both valves and actuators. Using value engineering as a systematic material selection approach shows that 25 Cr super duplex is an optimum material for valves in process services, such as valves for hydrocarbons and chemicals, if the hydrogen sulfide content in the oil is below the limit given in ISO 15156. A case study using a wall thickness and weight reduction approach—according to ASME sec.VIII instead of ASME B16.34—on large, heavy oil export pipeline ball valves is reviewed in this paper. A finite element analysis has been performed to ensure that the thickness of the valve is sufficient to withstand pipeline loads. Insufficient valve thickness can jeopardize the mechanical integrity of a valve and causes valve failure. SIL calculation is a major step in improving the safety and reliability of safety critical valves. A method of SIL calculation is implemented as per the IEC 61508 standard for oil export pipeline valves with an emergency shutdown function. Utilizing leakage monitoring and partial stroke testing increases the SIL along with safety and reliability.

Keywords Valves and actuators · Safety and reliability · Material failure · Corrosion · Design optimization · Offshore · SIL · Oil and gas industry

1 Introduction

A valve is a mechanical component in a piping system that is used for safety purposes, to open and close fluid passage, and to prevent the return of fluid and control flow (Nesbitt 2007; Smit and Zappe 2004; Sotoodeh 2020a). Valve failure is a big risk and a costly phenomenon in the offshore sector of the oil and gas industry with severe negative consequences, such as loss of assets, loss of production due to plant shutdowns, and health, safety, and environmental (HSE) issues. An actuator is a mechanical or electro-mechanical component installed on valves for automatic operation and control (Sotoodeh 2019a). The performance of valves is largely dependent on the actuators (Sotoodeh 2019a) Valves that are operated frequently, especially those that require a high amount of force for operation, are good candidates to be actuated. In addition, valves that are located in remote or hazardous areas with the potential for explosions are good choices for actuation (Sotoodeh 2019a).

Enhancing the safety and reliability of valves and actuators is necessary, since it reduces the likelihood of severe negative events, such as valve and actuator failure, in plants. Since the negative consequences of valve failure are severe, including the loss of assets and damage to the environment and human health, the main aim of this research is to provide approaches to improving the safety and reliability of valves and actuators in the offshore oil and gas industry. This paper investigates three areas of valve safety and reliability: material selection and design improvement, which are only applicable to valves, as well as safety integrity level (SIL) measurement and improvement, which is applicable

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✉ Karan Sotoodeh
karan_sqi@yahoo.com

[1] Department of Risk and Reliability Engineering, University of Stavanger, Stavanger, Norway

to both the valves and actuators. Figure 1 illustrates a heavily corroded part of a check valve, resulting in leakage and emission to the environment.

The paper is organized into four sections: introduction, methods and materials, results and discussion, and conclusion. It is important to consider this valve and actuator research in the context of both the subsea and topside sectors of the offshore oil and gas industry. An explanation of the methodologies for appropriate material selection, design improvement, safety measurement and enhancement, and testing are given in Sect. 2. The results are provided in Sect. 3, along with a discussion of them. Section 4 contains the conclusions of the paper and proposals for future research. After explaining the scope and background, the next paragraph provides more information about objective of research.

The main objective of this research is to increase the safety and reliability of industrial valves by improving valve design and material selection and by providing a systematic approach to measure the safety and reliability of valves through a safety integrity level study. Suitable material selection to minimize the risk of corrosion and failure due to mechanical loads can guarantee the safe and reliable operation of industrial valves during their operational lifetime. It should be noted that the focus of this paper is on valve material selection for offshore environments that are extremely harsh and corrosive. Design improvements in this research are done to optimize the weight and thickness of valves and are validated through a load analysis. An SIL study, which is typically combined with other safety and reliability methods, such as failure mode and effect analysis (FMEA), is of great assistance to engineers and researchers in identifying possible failure modes and their impact and finding solutions to mitigate them. The contribution of the research is provided in the last paragraph of this section.

Fig. 1 Heavy corrosion on the bottom of a check valve. (Courtesy: DNV)

This study is a response to valve and offshore industry needs and requirements. There is no prior research that connects safety and reliability with optimum design and material selection. Though an SIL study is not a new technique, this paper provides a practical way of performing an SIL study and using this approach in practice.

2 Materials and methods

Materials and methods contain three sections; material selection improvement, design optimization case study and finally safety integrity level measurement and improvement. Material corrosion and failure in the offshore oil industry have been addressed by several researchers (Sotoodeh 2018a, 2020b; Nustad 2015). The offshore environment is corrosive, containing chloride due to the presence of seawater, which can cause different types of corrosion, such as pitting and chloride stress cracking corrosion (CLSCC) (Sotoodeh 2020b; Spx 2008). As the name implies, pitting is localized corrosion that leads to the development of cavities or pits on metal surfaces (Sotoodeh 2020b; Spx 2008; Perry and Green 2019). Figure 2A illustrates pitting corrosion in the form of holes in piping. CLSCC is another type of corrosion that is caused and accelerated by applied or residual stress in materials, as illustrated in Fig. 2B (Sotoodeh 2020b; APV SPX 2008; Perry and Green 2019). Stresses that are introduced during fabrication due to welding and fast cooling, and stresses induced by the tightening of bolts and rivets are categorized as residual stress (Perry and Green 2019).

Corrosion and material failure are very costly. There are three main aspects to the cost of corrosion: capital expenses (CAPEX), operational expenses (OPEX), and health, safety and environment (HSE) costs. (Kermani and Harrop 1996) In addition, it is estimated that 25% of failures in the petroleum industry are associated with material failure due to corrosion (Kermani and Harrop 1996). According to research conducted by the National Association of Corrosion Engineers (NACE), in 2016, the cost of corrosion had reached more than US$2.5 trillion globally, which was evaluated as approximately 3.4% of the gross domestic product (GDP) of the world (National Association of Corrosion Engineers 2016). The serious negative impacts of corrosion on the economy and safety have caused engineers and scientists to make a significant effort to control and mitigate this phenomenon (Sotoodeh 2018b).

Systematic approaches to material selection for piping in offshore value engineering (VE) and techniques for order preference by similarity to ideal solution (TOPSIS) were reviewed and implemented in prior research (Sotoodeh 2018b; Ashbey 2005). The method for the selection of the

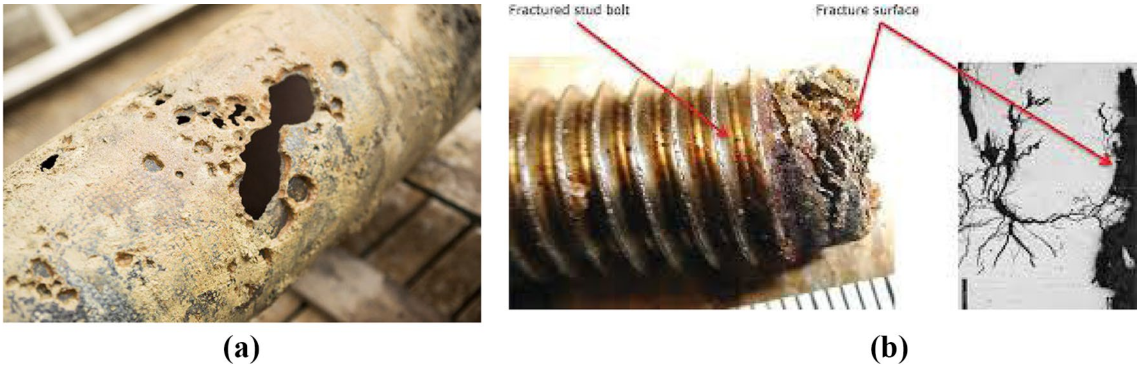

Fig. 2 **a** Piping pitting corrosion (Courtesy: Nu flow Midwest). **b** Valve bolt CLSCC (Courtesy: Valve World)

optimum material through value engineering involves four stages: In the first stage, called criteria definition, the objective is defined. The objective is to select the best material in terms of corrosion and its mechanical properties with the lowest cost. The second stage involves hierarchy determination in which different criteria for material selection, such as hardness, mechanical strength, and corrosion resistance are defined, and the hierarchical position and weight of each property (W_J) is estimated through an approach called pairwise comparison. Formula 1 shows that the sum of the weight values of the properties assigned to the material selection process should be equal to 1.

2.1 Formula 1: Total weight of parameters in value engineering method

$$\sum_{i=1}^{j} W_i = 1, \quad \text{where } i = 1, 2, 3, \ldots j \tag{1}$$

A pairwise comparison is performed in Table 1 between four material properties, P_1–P_4. Properties in each row are compared with properties in each column, one after the other. If a property in a row is more important than the property in a column, then the number 1 is entered into the table where they intersect. On the other hand, if a parameter in a row is less important than the parameter in the column, then the number 0 is entered into the table. If a material property is compared with itself, then no number is allocated. At the end, the total score for each property is calculated by adding the numbers in each row. The weighted score for each property is obtained through the ratio of the score of each property to the total score, which is seven in this case. Corrosion resistance is the most important material property according to the pairwise selection performed in Table 1.

The next stage is to assign a score for a material property value (C_{Jrate}) from 1 to 10 for each material candidate. For example, the yield strengths of carbon steel, stainless steel 316, 22Cr duplex, and 25 Cr super duplex are 30, 25, 65, and 90 ksi, respectively. Values for mechanical strength can be obtained from the American Society of Test and Materials (ASTM). Regarding the yield strength, the goal is to have it as high as possible. The maximum mechanical yield strength value, V_{Max}, is 90 ksi, and the minimum mechanical yield strength value, V_{Min}, is equal to 25 ksi. V_{Max} has a value of 10, and V_{Min} has a value of 1. Formula 2 is used to obtain the 1 to 10 scale value of each mechanical yield strength.

2.2 Formula 2: Scaling each material property between 1 and 10

$$\frac{C_{j\mathrm{Rate}} - 1}{10 - 1} = \frac{V_j - V_{\min}}{V_{\max} - V_{\min}} \tag{2}$$

According to Formula 2, the mechanical yield strength of carbon steel and 22 Cr duplex after scaling between 1 and 10 are 1.7 and 6.5, respectively.

The final stage in value engineering is to calculate the performance score of each material based on their

Table 1 Pairwise criteria comparison

Criteria	P_1	P_2	P_3	P_4	Total score	Weighted score
P$_1$: Yield stress (ksi)	P_1	0	1	1	2	0.29
P$_2$: Corrosion resistance	1	P_2	1	1	3	0.43
P$_3$: Ease of manufacturing	0	0	P_3	1	1	0.14
P$_4$: Availability	0	0	0	P_4	1	0.14
					7	1

properties such as corrosion resistance, mechanical strength, etc. using Formula 3.

2.3 Formula 3: Material performance calculation

$$\text{Performance} = \sum_{i=1}^{j} W_j x C_{j\text{Rate}} \tag{3}$$

Because the rating is set between 1 and 10 and the weights are between 1 and 100%, the performance value should be between 100 and 1000. The next section provides a case study about design optimization case study.

Design optimization of valves to improve safety and reliability can be implemented from different angles. However, the case reviewed in this section addresses the most important valve on an offshore platform. This valve is located on oil export pipelines and is the largest, heaviest, and most important valve, with the longest delivery time, in the offshore industry (Sotoodeh 2015). The valve in this case is 30 in. with a pressure class of 1500, which is equal to 250 bar pressure nominal (PN) (American Society of Mechanical Engineers 2004). ASME B16.34 is commonly used for the design of these valves, including the selection of wall thickness and the pressure rating (American Society of Mechanical Engineers 2004). The combination of its large size and high-pressure class makes this valve as heavy as 23 t, with a thickness of 126.2 mm according to the ASME B16.34 standard (American Society of Mechanical Engineers 2004). Alternatively, the wall thickness calculation method in ASME section VIII div.02 and Formula 4 reduce the weight of the valve by 9 t. (Sotoodeh 2018c; American Society of Mechanical Engineers 2012b).

2.4 Formula 4 (American Society of Mechanical Engineers 2012b): Wall thickness calculation for a pipeline valve, according to ASME sec.VIII div.02

$$t = \frac{D}{2}\left(e^{\frac{p}{s}} - 1\right) \tag{4}$$

where t = valve thickness (in.), D = valve diameter (inch) = 30″, p = valve design pressure (psi) = 250 bar = 250 × 14.5 = 3625 psi, S = Allowable stress (psi) for ASTM A216 WCB Body material of the valve = 20,000 psi, e = 2.7182.

The last section of methods and materials is about safety integrity level. The safety integrity level (SIL) is part of international standards, such as IEC 61,508, that provide suppliers and end users with a common framework for designing products and systems for safety-related applications (International Electrotechnical Commission 2010b). The SIL provides a scientific and numeric approach to designing safety systems, enabling the risk of failure to be quantified (Gulland 2004). The SIL is typically considered for valves that are categorized as safety critical valves (Rausand 2014). Safety critical valves are mainly those with an emergency shutdown (ESD) function. A safety critical valve is a part of a safety instrumented system (SIS). An SIS with safety critical valves includes three parts: multiple sensors, logic solver, and actuator valve (see Fig. 3) (Angelito 2017). The sensor is typically a pressure transmitter that monitors piping pressure against a predefined limit and send signals to the logic solver, where an appropriate course is taken based on the nature of the signal. The logic solver output in the form of an electrical signal results in an action taken by the final element, such as the shutting down of the process system through the closure of a valve. The SIL of the actuated valve in an SIS (e.g., SIL3), which is called the final element, should be defined in the project documents.

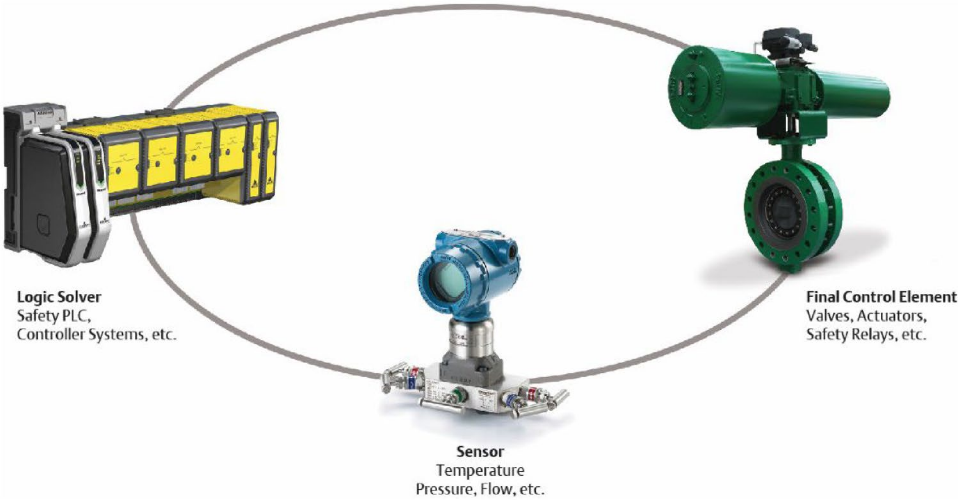

Fig. 3 SIS including a sensor, logic solver, and actuated valve (final element) (Courtesy: Emerson)

In fact, the reliability measurement of an SIS, including the final element of the SIS, an actuated valve, is performed through an SIL analysis (Sotoodeh 2019b).

The calculation of the SIL involves the identification of failure modes and their probabilities. In general, there are two failure modes: safe and dangerous. The probability of safe and dangerous failure modes is shown with λ_S and λ_D, respectively (International Electrotechnical Commission 2010a). The dangerous failure rate probability is divided into two probabilities, dangerous detected and dangerous undetected, whose failure rates are represented by λ_{DD} and λ_{DU}(International Electrotechnical Commission 2010a). The relationship between the total probabilities of failure, probabilities of the dangerous and safe failure rate is given in Formula 5. The relationship between the dangerous failure rate probability, dangerous detected failure rate probability and dangerous undetected failure rate probability is provided in Formula 6 as per IEC 61508 (International Electrotechnical Commission 2010a; Innal et al. 2016).

2.5 Formulas 5 and 6: Relationships between total, dangerous, and safe failure rate probabilities

$$\lambda_{TOTAL} = \lambda_S + \lambda_D \tag{5}$$

$$\lambda_D = \lambda_{DD} + \lambda_{DU} \tag{6}$$

where λ_{TOTAL}: total failure rate probabilities. λ_S: safe failure rate probability. λ_D: dangerous failure rate probability. λ_{DD}: dangerous detected failure rate probability. λ_{DU}: dangerous undetected failure rate probability.

The next step is to calculate the safety failure fraction (SFF) as per Formula 7, based on the failure probabilities. The SFF as calculated by Formula 7 is defined as the ratio of the safe failures plus dangerous detected failures to the total failure rate.

2.6 Formula 7: SFF Calculation

$$\mathrm{SFF} = \left(\frac{\lambda_S + \lambda_{DD}}{\lambda_S + \lambda_D}\right) = \left(\frac{\lambda_{TOTAL} - \lambda_{DU}}{\lambda_{TOTAL}}\right) \tag{7}$$

The last step is to correlate the SFF with the SIL, as per Table 2 from the IEC 61508 standard (International Electrotechnical Commission 2010a).

3 Results and discussion

This section contains the results and discussion of a material selection analysis and suggestions for valve design improvements based on a load analysis and an SIL study. The best choice of valve material for offshore applications from six candidates based on three important parameters and according to the value engineering method is made in this section. In addition, a valve wall thickness calculation, as per ASME section VIII div.02, is performed and a valve design based on the calculated thickness is validated according to a load analysis. In addition, SIL calculations are made and an analysis is performed to measure the safety and reliability of the valve.

Table 2 Correlation between the safety failure fraction (SFF) and the safety integrity level (SIL), as per IEC 61508

Safe failure fracture	Hardware fault tolerance—Type A		
	0	1	2
$\mathrm{SFF} < 60\%$	SIL 1	SIL 2	SIL 3
$60\% < \mathrm{SFF} < 90\%$	SIL 2	SIL 3	SIL 4
$90\% < \mathrm{SFF} < 99\%$	SIL 3	SIL 4	SIL 4
$\mathrm{SFF} \geq 99\%$	SIL 3	SIL 4	SIL 4

Table 3 contains three fundamental material properties for the material selection decision making process: mechanical yield strength, corrosion resistance and cost. Six types of materials that are common in process piping and valves in the offshore industry have been selected for value engineering (VE): carbon or low alloy carbon steel valve, stainless steel 316, 22Cr duplex, 25Cr super duplex, 6MO, and Inconel 625, which is a nickel alloy. It is important to bear in mind that the material of the valve is typically selected to be the same as the piping material (Standards Norway 1999).

All of the information in the table is quantified except for corrosion resistance. The following ratings are used to quantify the corrosion resistance of the metals (Sotoodeh 2018b; Perry 1999):

0: Unsuitable/Not applicable/Poor, 1: Poor to fair, 2: Fair, 3: Fair to good, 4: Good, 5: Good to excellent, 6: Excellent.

It is now possible to quantify the corrosion resistance data and place the corresponding number in Table 3 for each corrosion resistance quality. The next step is to convert each value to a number from 1 to 10. An important consideration is that mechanical strength and corrosion resistance should be high and relative cost should be low. Thus, 25 Cr super duplex, which has highest mechanical strength at 90 ksi, gets a score of 10. However, carbon steel has the lowest cost, equal to 1, and gets the highest score, 10, for the relative cost. The scaling from 1 to 10 for each material property value, as per Formula 2, provided in Table 3 is given in Table 4.

In this section, a pairwise comparison of three material properties, as per Table 5, is conducted to obtain the weight of each property, as is done in Table 1.

The next step is to calculate quantitative performance (Table 6) for each material type, according to Formula 3. The material names are abbreviated in Table 6 as *C* for carbon steel, *A* for stainless steel 316, *D* for 22Cr duplex, *S* for

Table 3 Yield strength, corrosion resistance, relative cost of candidate materials for process piping and valves

Material	Mechanical strength (yield) Ksi	Corrosion resistance	Relative cost
Carbon and low-temperature carbon steel	30	Poor to fair (1)	1
Stainless steel 316	25	Poor to fair (1)	3
22Cr Duplex stainless steel	65	Good (4)	4
25Cr Super duplex-stainless steel	90	Good to excellent (5)	5
6MO	44	Good to excellent (5)	6
Nickel alloy-Inconel 625	60	Excellent (6)	10

Table 4 Scaling of yield strength, corrosion resistance, and relative cost to a 1 to 10 score for candidate materials for process piping and valves

Material	Mechanical strength (yield) ksi	Corrosion resistance	Relative cost
Carbon and low-temperature carbon steel	1.7	1	10
Stainless steel 316	1	1	8
22Cr Duplex stainless steel	6.5	6.4	7
25Cr Super duplex-stainless steel	10	8.2	6
6MO	3.6	8.2	5
Nickel alloy-Inconel 625	5.8	10	1

Table 5 Pairwise criteria comparison

Criteria	P_1	P_2	P_3	Total score	Weighted score
P_1: Yield stress (ksi)	P_1	0	1	1	0.25
P_2: Corrosion resistance	1	P_2	1	2	0.50
P_3: Relative cost	0	0	P_3	1	0.25
				4	1

25Cr super duplex, *M* for 6Mo, and *N* for Inconel 625. The calculations in Table 6 indicate that 25Cr super duplex is the optimum material for process piping as well as valves. It should be noted that a 25Cr super duplex valve typically has a 25Cr super duplex body, a bonnet, and internals (Standards Norway 1999).

This paragraph provides the discussion related to material selection case for industrial valves. The most important finding is that super duplex is the optimum material for process piping and valves in process systems. Process piping and valves are those that are used for oil and gas services as well as chemicals. Using super duplex can provide sufficient corrosion resistance for process piping and valves to prevent valve failure due to corrosion and loads, which is essential to guarantee the safety and reliability of the valves. There are, however, three limitations associated with using 25Cr super duplex that were not considered in the results section. The limitations are derived from the Norsok M-001 Norwegian material selection standard, the ASME B31.3 process piping code, and the ISO 15156 standard for the use of materials in a sour service H_2S-containing environment (Standards Norway 2004; American Society of Mechanical Engineers 2012a; International Organization for Standardization 2015). The limitations of 25Cr super duplex are that super duplex is suitable for a minimum design temperature of – 46 ℃ (American Society of Mechanical Engineers 2012a), a maximum operating temperature without coating of 110 ℃, (Standards Norway 2004) and a maximum H_2S pressure of 3 psi (International Organization for Standardization 2015). In fact, super duplex valves could be the optimum choice

Table 6 Material performance calculation

Mat	C	A	D	S	M	N
P_1 rate	1.7	1	6.5	10	3.6	5.8
P_1 weight	25	25	25	25	25	25
P_2 rate	1	1	6.4	8.2	8.2	10
P_2 weight	50	50	50	50	50	50
P_3 rate	10	8	7	6	5	1
P_3 weight	25	25	25	25	25	25
Total score	342.5	275	657.5	810	625	670

for oil and gas services with lower amounts of H_2S, such as in the oil and gas fields on the Norwegian continental shelf.

Another limitation of the model is that not all of the parameters are taken into account. However, the proposed model can be developed further with more material properties taken into account. Material selection plays an important role in the design optimization and corrosion prevention of valves. Looking at a very big subsea project in Africa, where ENI was the client, 838 valves out of 1058 were made of 25 Cr super duplex stainless steel. Carbon steel with a 3 mm cladding of Inconel 625 was used for 220 valves that were used for high hydrogen sulfide containing service. A final limitation of the model is that it only addresses the process piping and valves. Utility services, such as seawater, is a corrosive fluid, and additional research is proposed on material selection for valves used for utility services, such as sea water.

This section gives detail information about weight and design optimization case study results for the large pipeline valve. Using the values Formula 4 provides, the wall thickness of the 30 in., class 1500 valve based on ASME sec.VIII div.02 is equal to 2.98 in. (75.71 mm). Figure 4 compares the weight and wall thickness values for the export line pipeline valve at a 30 in. size and ASME pressure class 1500, as per ASME B16.34 and ASME sec.VIII, div 0.02 (Sotoodeh 2018c). Using the method in ASME section VIII div.02 to calculate the wall thickness of the oil export pipeline valve results in a thinner valve and a 9 t wall thickness reduction.

Applying a real load test (see Fig. 5) or other tests, such as a pressure test, to the valve after assembly may reveal deformation problems too late. In addition, the tests may damage the valve. Thus, the recommendation of this paper, based on some industrial projects in Norwegian offshore industry, is to apply a finite element analysis (FEA) to the valves during the design phase and before the start of manufacturing. The different loads to be applied to the valves could be derived from stress analysis software. Figure 5A, B illustrates the result of an FEA. Three stress values, P_m (general preliminary membrane stress), P_I (local preliminary membrane stress), and P_b (preliminary bending stress), have been determined for two sections of the body of the valve at 200 ℃, as per Table 7.

The body of the valve is carbon steel ASTM A216 WCB, and the maximum design temperature is 200 ℃, which is considered the worst-case-scenario temperature for the loads. The allowable stress (parameter S) on a valve body of ASTM A216 WCB at 200 ℃ is 152 Mpa (American Society of Mechanical Engineers 2012a).

Three conditions should be met, according to ASME sec. VIII, to ensure that the thickness of the valve is sufficient: First, $P_m < S$; second, $P_I < 1.5S$; and third, P_m or $P_I + P_b < 1.5\ S$.

$P_m = 120$ & $123 < 152$, $P_I = 70$ & $75 < 1.5 \times 152 = 228$, $P_I + P_b = 190$ & 225 & < 228.

Thus, all three conditions are satisfied, and the thickness of the valve body is sufficient in both sections, as illustrated in Fig. 6A, B. Next paragraph is the discussion section related to weight and design optimization of the industrial valve.

The most important finding in this section is to use ASME sec.VIII, div.2 for the wall thickness calculation of pipeline valves in the offshore industry to reduce the wall thickness and weight of the valves. It is very important to reduce weight on offshore platforms, since there is a limited weight capacity on the platforms. To date, there have been no studies on this, except for a paper published in an ASME journal, which is cited here (Sotoodeh 2018c). The significance of the results is, however, not limited to a weight reduction approach to export pipeline valves. The results, involving a method from ASME sec.VIII is used to validate the calculated thickness based on the applied loads and FEA, represent another important contribution. Insufficient

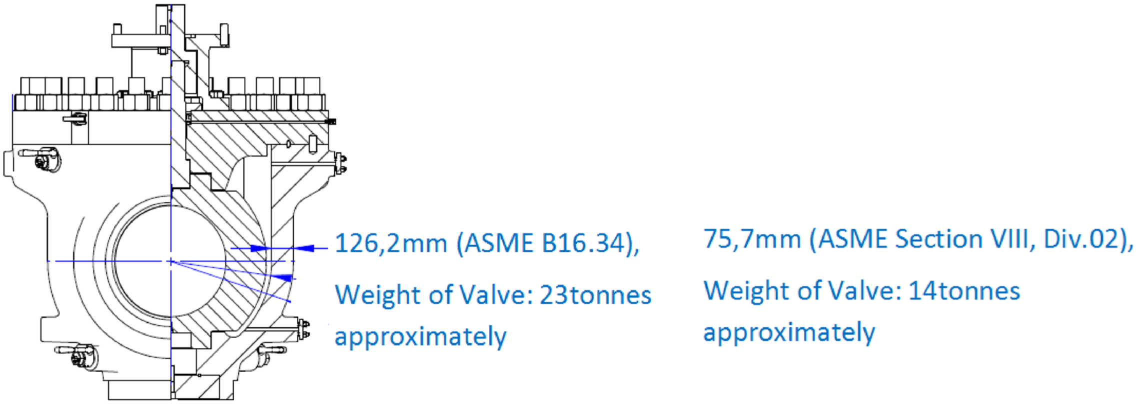

Fig. 4 30 in., CL1500 oil pipeline valve wall thickness and weight reduction using the ASME sec VIII div.02 method compared to ASME B16.34 (Courtesy: ASME)

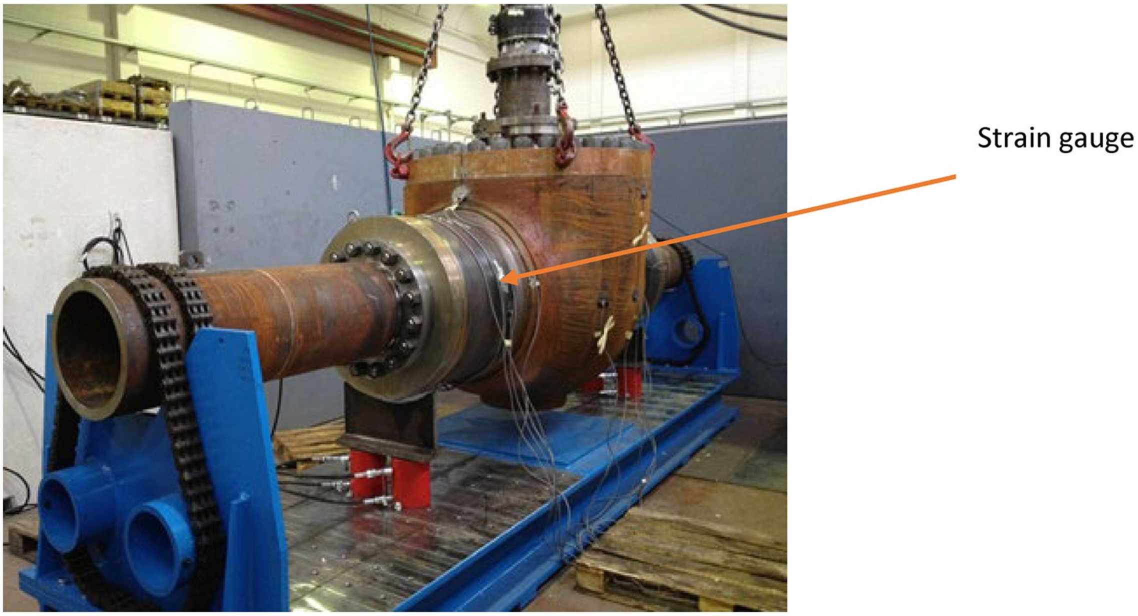

Fig. 5 Load test including a bending moment test on a pipeline valve. (Courtesy: Valve Magazine)

Table 7 Stress value results for two sections of the body of the 30 in., CL1500 valve (Courtesy: ASME)

Section	P_m (Mpa)	P_l (Mpa)	P_b (Mpa)
1	120	70	120
2	123.8	75	150

thickness of valves jeopardizes the structural integrity of these components, which results in emissions, environmental pollution, loss of assets, and other negative consequences. The proposed approach to weight reduction of valves has been applied on several offshore platforms in the Norwegian offshore industry, the including Johan Sverdrup project, which is one of the biggest offshore petroleum fields in the history of Norway. One limitation of this method is that it focuses on weight reduction of the body of a valve; weight reduction of other components of a valve, such as a bonnet or ball, are excluded from this research. The next section contains results and discussion associated with SIL measurement and improvement for the valve.

A 20 in., CL1500 ball valve with an emergency shutdown function was installed on a gas export pipeline. SIL analysis was performed on this valve to ensure the safety

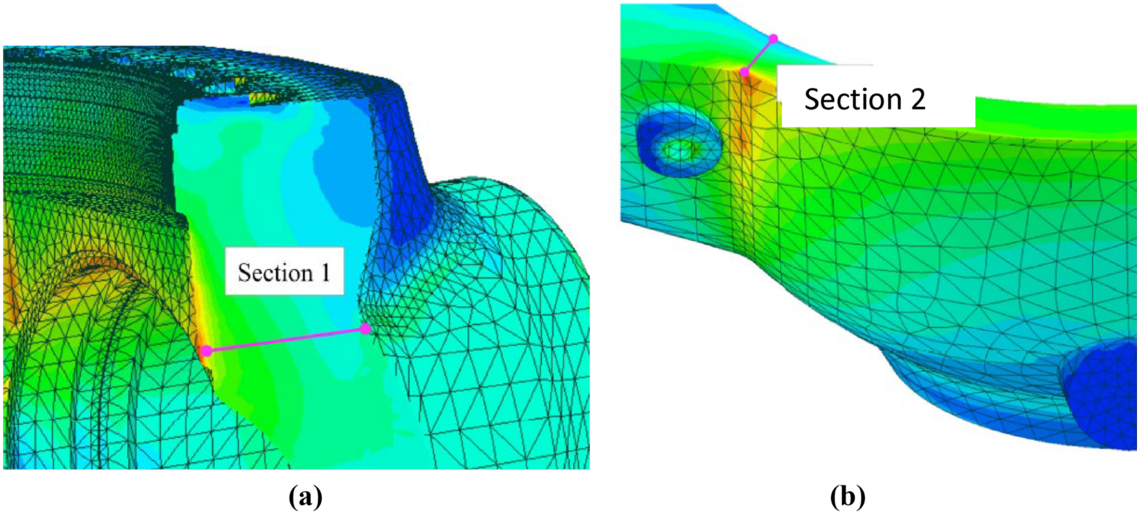

Fig. 6 **A**, **B** FEA load distribution on sections 1 and 2 of the 30 in., CL1500 valve. (Courtesy: ASME)

Table 8 Failure rates of a 20 in. CL1500 ball valve, actuator, and control panel on a gas export line

Component	λ_{DU}	λ_{Total}
TE 20 in. class 1500 ball valve	2.57E−08	8.56E−08
Actuator	1.9E−09	2.12E−08
Control panel	4.00E−011	9.03E−08
Total values	2.76E−08	1.97E−07

and reliability of the valve. The actuated valve contained three elements for SIL study: a valve, an actuator, and a control panel. Data related to the probability of failure rates for the valve, actuator, and control panel, as provided by the valve and actuator manufacturers, is shown in Table 8.

Using Formula 7, it is possible to calculate and obtain a value for SFF:

$$\begin{aligned} \text{SFF} &= \left(\frac{\lambda_S + \lambda_{\text{DD}}}{\lambda_S + \lambda_D}\right) = \left(\frac{\lambda_{\text{TOTAL}} - \lambda_{\text{DU}}}{\lambda_{\text{TOTAL}}}\right) \\ &= \left(\frac{1.97\text{E}-07 - 2.76\text{E}-08}{1.97\text{E}-07}\right) \\ &= \left(\frac{1.694\text{E}-07}{1.97\text{E}-07}\right) = 86\% \end{aligned} \tag{7}$$

If the hardware fault tolerance is assumed to be zero, the SIL corresponding to an 86% safety failure fraction (SFF) is SIL2 (see Table 2). SIL2 may not be reliable enough for an important actuated valve with an emergency shutdown function. Therefore, two main approaches, partial stroke testing and online monitoring, are proposed to increase the reliability of the actuated valves (Lundteigen and Rausand 2007; Sotoodeh 2020c).

The most important finding in this section is the importance of measuring, interpreting, and increasing the safety integrity level of safety critical valves. Increasing the SIL means improving the safety and reliability of valves, actuators, and control systems. The results show that a 20 in. ball valve in a gas export pipeline can achieve a SIL2, which may not be sufficient. Thus, partial stroke testing and online monitoring are proposed to increase the reliability of the system. Partial stroke testing is a technique that is regularly practiced in oil and gas industries to test the emergency shutdown (ESD) valve by closing a certain percentage of the valve and stopping any flow through the pipeline. This technique can detect some dangerous failures and improves the SIL. Online valve monitoring, specifically "ValveWatch," is a state-of-the-art method for improving the reliability of safety critical valves during operation (Sotoodeh 2020c). ValveWatch refers to series of sensors installed on industrial valves to detect possible failures, such as leakage from packing and seat, stem bending damage, etc. at early stage before the failures are getting more critical. This well-known method has been used for almost two decades to detect the potential failures of valves, actuators, and control systems (Sotoodeh 2020c).

4 Conclusions

Failures of valves and actuators in the offshore industry have negative impacts, such as a loss of assets, production losses, and HSE problems. Three aspects of the improvement of the safety and reliability of valves and actuators were introduced in this paper: material selection, design optimization, and safety integrity level measurement and improvement. Value engineering as a systematic material selection approach was introduced and implemented to identify optimum materials in terms of mechanical strength, corrosion resistance, and cost. 25Cr super duplex is an optimum material for process piping and valves if the concentration of hydrogen sulfide inside a fluid service is less than the limit set by ISO 15156 for 25Cr super duplex. In addition, a finite element analysis approach plus a criterion based on ASME sec.VIII, div.02 were proposed to assess the structural integrity of pipeline valves. The importance of SIL measurement, as per IEC 61508, as well as SIL improvement techniques such as online monitoring and partial stroke testing was demonstrated. A SIL study and analysis was performed on a 20″ CL1500 gas export pipeline ball valve to ensure the safety and reliability of the valve.

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