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Risk Assessment of FCAW-GS Welding on TKY Joints in Offshore Wind Farm Jacket

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Abstract— **Offshore wind farms are vital in supporting the global energy transition, requiring high structural integrity, particularly in welded T-K-Y joints of jacket foundations. These joints must endure harsh marine environments and dynamic loads, making weld quality a critical factor. This research aims to identify, analyze, and mitigate the risks associated with Flux Cored Arc Welding – Gas Shielded (FCAW-GS) on T-K-Y joints in offshore wind farm jacket construction using the Failure Mode and Effect Analysis (FMEA) method. The study used expert surveys to assess risk factors based on Severity (S), Occurrence (O), and Detection (D), which were quantified into Risk Priority Numbers (RPN). A 5x5 risk matrix was employed for visualization, and mitigation strategies were developed based on the highest RPN values. The most significant risks identified were: inadequate preheating in T-joints (RPN 158.33), poor inter-pass cleanliness in K-joints (RPN 308.00), and similar cleanliness issues in Y-joints (RPN 264.44). After implementing risk mitigation measures such as welder training and strict inter-pass cleaning procedures, the weld rejection rate was reduced to only 1.2% out of 998 joints. The application of FMEA proved effective in prioritizing and controlling welding risks. This structured risk management approach—aligned with ISO 31000:2018—contributed to improved weld quality and reliability in offshore wind farm construction.**

Keywords— Risk assessment, FCAW-GS, T-K-Y joints, Offshore wind farm, FMEA, RPN

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I. INTRODUCTION

Offshore wind energy has emerged as a critical solution in the global pursuit of carbon neutrality, offering sustainable alternatives to fossil fuels. A core component of this infrastructure is the jacket substructure, designed to endure complex marine conditions. The integrity of this structure heavily relies on the quality of welded connections, especially T-K-Y joints, due to their exposure to dynamic loads. The complexity of welding these joints using Flux Cored Arc Welding – Gas Shielded (FCAW-GS) presents several challenges, including defects such as porosity and incomplete fusion. Although the FMEA method has been applied in other welding contexts, there is a research gap in applying it specifically to FCAW-GS welding on TKY joints within offshore jacket construction. This study addresses this gap by analyze key risk factors in FCAW-GS welding failure for T-K-Y joints and proposing mitigation strategies to improve reliability and safety in offshore structures.

According to [1], failures in wind turbine components can result in serious operational disruptions as well as increased repair costs and downtime, making risk management a crucial aspect in the development of offshore wind farms. Meanwhile, FCAW-GS (Flux Cored Arc Welding - Gas Shielded) welding is widely used in T-K-Y joints because it has advantages in terms of productivity, deep penetration, and arc stability, especially in outdoor environments. However, this method also holds high potential risks, such as weld defects, incomplete fusion, or porosity that can reduce joint quality and cause project delays due to repeated repairs [2].

Academically, the Failure Mode and Effect Analysis (FMEA) approach has proven effective in identifying and evaluating potential failures in various engineering processes, including welding. FMEA assesses risk based on three main parameters: Severity (S), Occurrence (O), and Detection (D). A study by [3] showed that the application of FMEA to boiler welding successfully identified porosity as the dominant defect due to welder skill, electrode condition, and machine settings. Meanwhile, [4] used FMEA to analyse delays in ship repair, resulting in the lack of auxiliary tools and problems in the welding process being the main causes of risk.

However, there is still a research gap in the specific application of FMEA to the FCAW-GS welding process of T-K-Y joints in offshore wind farm jacket structures. Most previous studies have not specifically highlighted the application of the FMEA method to complex structural welded joints in an offshore environment, particularly in the T-K-Y joints

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configuration using the FCAW-GS welding process. Failure Mode and Effect Analysis (FMEA) is a systematic method designed to identify potential failures in a system, product, or process and evaluate their impact based on three main parameters: Severity, Occurrence, and Detection.

Figure 1. Construction of Offshore Wind Farm Jacket (Source: Changhua Project in Batam)

This method provides a numerical value known as the Risk Priority Number (RPN), which is the product of the three parameters which are used to determine which risk priorities should be addressed immediately [3], [1]. However, there is still a lack of research that focuses specifically on the risk of FCAW-GS welding of T-K-Y joints in offshore wind farm projects. Therefore, this study aims to fill the gap by providing a quantitative analysis of FMEA-based welding risks focusing on the complex joint geometry of TKY.

II. METHOD

This study applied a structured FMEA approach, supported by primary data collected via surveys and interviews from experts involved in offshore jacket fabrication in Batam (2023–2025). The risk factors were identified and rated based on severity (S), occurrence (O), and detection (D), and the RPN values were calculated using Equation [4]. Results were mapped using a 5x5 risk matrix (Figure 2), and the research methodology is outlined in the process flow (Figure 3). Quantitative results from survey responses are presented in Tables 2–10 for T, K, and Y joints, while mitigation strategies are summarized in Table 12. The FMEA framework used here enables structured prioritization of risk across joint types based on empirical data.

$$\text{Mean} = \frac{\sum \text{(S) or (O) or (D)}}{\sum \text{The total number of respondents}} \quad ...... [4]$$

So, based on the formula above, the average score was calculated for each FCAW-GS welding risk factor in each T, K, and Y joints. Furthermore, after obtaining the average value for each parameter, the RPN calculation for each risk is carried out using the Risk Priority Number (RPN) formula by multiplying the three values for each risk agent factor.

RPN = (S) x (O) x (D) .... [4]

The Risk Priority Number (RPN) is calculated by multiplying three factors: the severity of the impact (Severity), the likelihood of the failure occurring (Occurrence), and the ability to detect the failure (Detection). This RPN value is used to determine the order of risk prioritization. The higher the RPN value, the more important the risk is to be addressed immediately. Risks with the highest RPN value will be looked for solutions first so that they can be controlled appropriately.After obtaining the Risk Priority Number (RPN) value from the FMEA analysis, each risk factor in the FCAW-GS welding process was then grouped into a 5x5 risk matrix. This matrix uses two main parameters to map and prioritize risks, namely the severity of the impact (Severity) and the probability of occurrence (Occurrence).

However, as explained by [5], the 5x5 risk matrix approach does not include the Detection aspect (ability to detect failures), which is an important part of FMEA. As a result, not all risk information generated from FMEA can be fully accommodated in the risk matrix mapping. Nevertheless, this mapping is still helpful to visualize the risks based on the two main dimensions (S and O), as well as to assist in determining control priorities to reduce the likelihood of FCAW-GS welding failures, especially in T, K, and Y joints in construction structures.

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Level Risk Mapping	**Severity (Impact)**				
Occurance (Probabilities)	1	2 - 3	4 - 5	6 - 8	9 - 10
1	Low	Low	Low	Medium	Medium
2 - 3	Low	Low	Medium	Medium	High
4 - 5	Low	Low	Medium	High	High
6 - 8	Low	Medium	Medium	High	High
9 - 10	Low	Medium	High	High	High

Figure 1. Risk Level Mapping Scale (Source: Ariany et.al, 2003)

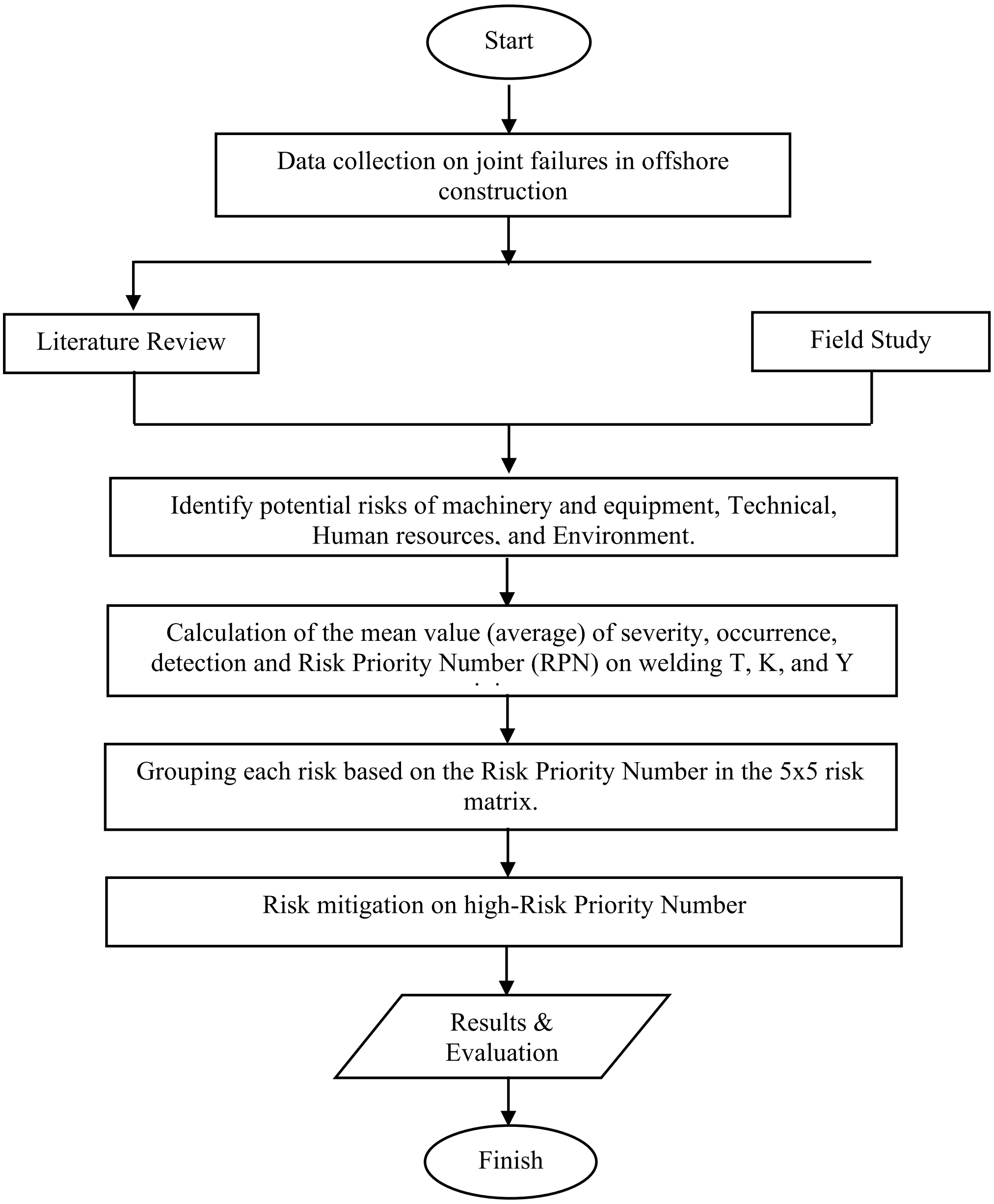

Figure 3. Flow Chart of Research Methodolo

a. Research model

The research model used is primary data research, meaning that data is collected directly from the first source. In this case, data collection was conducted through a survey, namely by distributing questionnaires to the research participants who were directly involved in the process under study, namely Qualified Welders, Welding Inspectors and Welding Engineers with a minimum experience of 7 years in the Offshore Wind farm jacket construction project carried out in Batam from November 2023 to February 2025.

b. Research Design

The research design was organized with the following steps:

a. The FMEA model is used to identify risks that may occur during the work process.

b. Risk factors were determined based on the stages in the FCAW-GS welding process, specifically on the three types of joints, namely T-Joint, K-Joint, and Y-Joint.

c. Measurement of the causes of risk in the welding process is carried out using the FMEA theory approach.

It describes how the research steps are systematically designed to understand and assess potential risks in welding.

c. Data analysis techniques

This study's data collection techniques involved field surveys, which collect information directly from the activity sites or the respondents. After the data were collected, it will be analyzed using the Failure Modes and Effects Analysis (FMEA) method to determine and evaluate potential problems or risks that may occur.

d. Risk mapping

Risk mapping using a 5x5 matrix is a method for determining which risks need to be addressed first. The assessment is based on two main factors, namely the level of impact (severity) and the likelihood of Occurrence.

e. Mitigation strategy

Mitigation strategies are focus on handling the risks with the highest RPN in each connection, because these risks have the potential to cause the greatest loss or the most significant disruption to the quality of welding results.

f. Conclusions

After the process of assessing the various possible problems - from assessing the severity to determining which ones need to be addressed first - this research resulted in conclusions about the types of risks that are most influential in FCAW-GS welding work using FMEA

g. Evaluation

Evaluation of the effectiveness of the application of FMEA to the total T, K, and Y joints was carried out to assess how well this method could identify, prioritize, and help reduce the potential risk of welding failure by comparing at the results of rejected welds to total welds.

III. Results and Discussion

This research was conducted during the construction of a 4 Legs Jacket with a size of 113 metres high and weighing 3250 metric tons built in Batam.

TABLE 1.
RISK CAUSES OF FCAW-GS WELDING IN T, K, & Y JOINTS

No.	Criteria Risk	Risk Event	Code	Risk Agent
1	Problems with Welding Machines	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	T1 / K1 / Y1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.
		Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	T2 / K2 / Y2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.
2.	Technical Risk	Errors in Fit-Up	T3 / K3 / Y3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.
		Cleanliness Between Weld Seams	T4 / K4 / Y4	Poor cleanliness between welding seams can lead to contamination or defects in the resulting joint.
3	Human Resources Risk	Fitter Skills in Joint Fit-Up	T5 / K5 / Y5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.
		Welders' Capabilities and Skills	T6 / K6 / Y6	Low skill levels of welders or inexperience can reduce the quality of welds.
4	Environmental Risks	Weather Conditions	T7 / K7 / Y7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.
		Preheat Temperature	T8 / K8 / Y8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.

The analysis reveals that insufficient inter-pass cleanliness and inadequate preheating are consistently among the highest risks across T, K, and Y joints. The RPN value for cleanliness in K joints reaches 308, underscoring the necessity of strict slag removal between passes. Similarly, poor preheat in T joints leads to the highest RPN of 158.33, indicating critical thermal preparation failure. These findings highlight not only the critical areas requiring attention but also validate the use of FMEA in welding risk prioritization under offshore conditions. The success of mitigation evidenced by the low reject rate of 1.2% demonstrates the effectiveness of structured risk management in real-world fabrication. The novelty of this study lies in combining quantitative RPN assessment with contextualized offshore construction data.

The interview data is then compiled and used as a reference in the preparation of the questionnaire so that it can be known how much the severity, occurrence, and detection values are.

Table 1 in this juournal article presents the classification and description of risk causes occurring in the Flux Cored Arc Welding – Gas Shielded (FCAW-GS) process on T-K-Y joints of offshore wind farm jacket structures. This table represents the initial identification of risks prior to the implementation of the Failure Moode and Effect Analysis (FMEA).

The following is a recapitulation of the average value for each welding risk factor in each T, K, and Y joint

TABLE 2.
AVERAGE OCCURANCE (O), DETECTION (D), AND SEVERE (S) VALUES OF RISK CAUSES OF FCAW-GS WELDING IN THE T JOINT

No.	Risk Event	Code	Risk Agent	Average O	Average D	Average S
1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	T1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	2.333	4	6.333
	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	T2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	3	5	6.333
2.	Errors in Fit-Up	T3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	2	3.333	5.333
	Inter-pass cleanliness	T4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	5.667	3.667	5.667
3	Fitter Skills in Joint Fit-Up	T5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	3.667	3.667	6.333
	Welders' Capabilities and Skills	T6	Low skill levels of welders or inexperience can reduce the quality of welds.	3	3.333	5.333
4	Weather Conditions	T7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	4.667	2.667	5
	Preheat Temperature	T8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	5	5	6.333

TABLE 3
. MEAN OCCURRENCE (O), DETECTION (D), AND SEVERE (S) VALUES OF RISK CAUSES OF FCAW-GS WELDING AT K JOINT

No.	**Risk Event**	**Code**	**Risk Agent**	**Average O**	**Average D**	**Average S**
1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	K1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	2.333	4	6
	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	K2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	2.333	5	6.667
2.	Errors in Fit-Up	K3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	4.667	3.667	6.667
	Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	7.333	6	7
3	Fitter Skills in Joint Fit-Up	K5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	4.667	5	7
	Welders' Capabilities and Skills	K6	Low skill levels of welders or inexperience can reduce the quality of welds.	5.333	5	6
4	Weather Conditions	K7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	6	4	5.667
	Preheat Temperature	K8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	4,333	5	7

Table 3 shows the average value of each factor. Lack of cleanliness between weld pass can cause contamination or defects in the joint, which is the highest risk factor in the K joint. The results show an Occurrence (O) value of 7.33, Detection (D) of 6.00, and Severity (S) of 7.00, which are the highest factors causing FCAW-GS welding risks.

TABLE 4.
AVERAGE OCCURRENCE (O), DETECTION (D), AND SEVERE (S) VALUES OF THE RISK CAUSES OF FCAW-GS WELDING AT THE Y JOINT

No.	Risk Event	Code	Risk Agent	Average O	Average D	Average S
1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	Y1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	2.333	4	6.333
	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	Y2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	2.333	5	6.333
2.	Errors in Fit-Up	Y3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	3	4	7
	Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	7	5,667	6.667
3	Fitter Skills in Joint Fit-Up	Y5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	4.667	4.667	6.333
	Welders' Capabilities and Skills	Y6	Low skill levels of welders or inexperience can reduce the quality of welds.	5	5.333	6
4	Weather Conditions	Y7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	5.667	4	5.667
	Preheat Temperature	Y8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	4	5	6

Table 4 shows the average value of each factor. Insufficient cleanliness between welding seams can cause contamination or defects in the joint, which is the highest risk factor in joint Y. The results show an Occurrence (O) value of 7.00, Detection (D) of 5.66, and Severity (S) of 6.66, which are the highest factors causing risk in FCAW-GS welding.

Level of risk	**Severity (Impact)**				
Occurance (Probabilities)	1	2 – 3	4 - 5	6 - 8	9 - 10
1					
2 - 3					
4 - 5					
6 - 8			T3, T6, T7	T1, T2, T4, T5, T8	
9 - 10					

Figure 4. Risk mapping of FCAW-GS welding in T-joints

TABLE 5.
HIGH CATEGORY RISK MAPPING OF FCAW-GS WELDING IN T-JOINTS

Code	Risk Agent
T1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.
T2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.
T4	Poor cleanliness between welding seams can lead to contamination or defects in the resulting joint.
T5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint
T8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.

Table 5 above shows that based on code T1, T2, T4, T5, and T8 are high risks based on the value of the Occurrence (probability of failure) and Severity (level of work impact) level.

Level of risk	Severity (Impact)				
Occurance (Probabilities)	1	2 - 3	4 - 5	6 - 8	9 - 10
1					
2 - 3					
4 - 5					
6 - 8				K1, K2, K3, K4, K5, K6, K7, K8	
9 - 10					

Figure 5. Risk mapping of FCAW-GS welding in the K joint

Figure 5 shows that based on the value of the Occurrence (probability of failure) and Severity (level of work impact) levels, the high-risk category has 8 risks as follows:

TABLE 6.
HIGH CATEGORY RISK MAPPING OF FCAW-GS WELDING IN K JOINT

Code	Risk Agent
K1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.
K2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.
K3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.
K4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.
K5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.
K6	Low skill levels of welders or inexperience can reduce the quality of welds.
K7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.
K8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.

Table 6 above shows that based on the code, K1 - K8 are high risks based on the value of the Occurrence (probability of failure) and Severity (level of work impact) levels,

Level of risk	Severity (Impact)				
Occurance (Probabilities)	1	2 - 3	4 - 5	6 - 8	9 - 10
1					
2 - 3					
4 - 5					
6 - 8				Y1, Y2, Y3, Y4, Y5, Y6. Y7, Y8	
9 - 10					

Figure 6. Risk mapping of FCAW-GS welding in Y-joints

Figure 6 shows that based on the value of the Occurrence (probability of failure) and Severity (level of work impact) levels, the high-risk category has 8 risks as follows:

TABLE 7.
HIGH CATEGORY RISK MAPPING OF FCAW-GS WELDING IN THE Y JOINT

Code	Risk Agent
Y1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.
Y2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.
Y3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.
Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.

CONTINUED - TABLE 7.
HIGH CATEGORY RISK MAPPING OF FCAW-GS WELDING IN THE Y JOINT

Y5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.
Y6	Low skill levels of welders or inexperience can reduce the quality of welds.
Y7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.
Y8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.

After the average data of Severity (S), Occurrence (O), and Detection (D) values for each risk factor of FCAW-GS welding of T-K-Y joints is obtained and risk mapping is carried out. Then, the Risk Priority Number (RPN) calculation is carried out based on each value of the risk factor.

Based on the RPN results, the risk priority order is compiled, and the appropriate solution is determined as a handling step.
The formula for calculating the Risk Priority Number value is:
RPN= (S)× (O)× (D) ....[4]

TABLE 8.
RPN VALUE ON THE RISK CAUSES OF FCAW-GS WELDING IN THE T JOINT

No.	Criteria Risk	Risk Event	Code	Risk Agent	RPN
1	Problems with Welding Machines	Machines that are not functioning properly or are damaged can cause interference with weld quality.	T1	Machines that are not functioning properly or are damaged can cause interference with weld quality.	59.111111
		Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	T2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	95.00
2.	Technical Risk	Errors in Fit-Up	T3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	35.555556
		Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	117.74074
3	Human Resources Risk	Fitter Skills in Joint Fit-Up	T5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	85.148148
		Welders' Capabilities and Skills	T6	Low skill levels of welders or inexperience can reduce the quality of welds.	53.333333
4	Environmental Risks	Weather Conditions	T7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	62.222222
		Preheat Temperature	T8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	158.33333

The Risk Priority Number (RPN) value for FCAW-GS welding in the T joint (Table 8) shows the highest result at the risk of insufficient material temperature before welding with an RPN value of 158.33, while the lowest value is at the risk of a machine that is not functioning properly with an RPN value of 35.55.

The Risk Priority Number (RPN) value for FCAW-GS welding in joint K (Table 9) shows the highest result at the risk of lack of cleanliness between the welding seams and an RPN value of 308.00, while the lowest value is at the risk of a machine that is not functioning properly with an RPN value of 56.00.

TABLE 9.
RPN VALUE ON THE RISK CAUSES OF FCAW-GS WELDING AT JOINT K

No.	Criteria Risk	Risk Event	Code	Risk Agent	RPN
1	Problems with Welding Machines	Machines that are not functioning properly or are damaged can cause interference with weld quality.	K1	Machines that are not functioning properly or are damaged can cause interference with weld quality.	56,00
		Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	K2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	77.77777778
2.	Technical Risk	Errors in Fit-Up	K3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	114.0740741
		Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	308000
3	Human Resources Risk	Fitter Skills in Joint Fit-Up	K5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	163.3333333
		Welders' Capabilities and Skills	K6	Low skill levels of welders or inexperience can reduce the quality of welds.	160.00
4	Environmental Risks	Weather Conditions	K7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	136.00
		Preheat Temperature	K8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	151.6666667

TABLE 10.
RPN VALUE ON THE RISK CAUSES OF FCAW-GS WELDING IN Y JOINT

No.	Criteria Risk	Risk Event	Code	Risk Agent	RPN
1	Problems with Welding Machines	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	Y1	Machines that are not functioning correctly or are damaged can cause interference with weld quality.	59.111111
		Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	Y2	Fluctuations or instability of amperage during welding can affect the quality of the resulting weld.	73.888889
2.	Technical Risk	Errors in Fit-Up	Y3	Errors or mismatches in joint adjustment can cause defects or problems in the weld.	84.00
		Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	264.44444
3	Human Resources Risk	Fitter Skills in Joint Fit-Up	Y5	The skill of the fitter in performing an inappropriate fit-up can affect the quality of the welded joint.	137.92593
		Welders' Capabilities and Skills	Y6	Low skill levels of welders or inexperience can reduce the quality of welds.	160.00
4	Environmental Risks	Weather Conditions	Y7	Inclement weather (wind, humidity, or extreme temperatures) can affect the stability of the arc shield and weld quality.	128.44444
		Preheat Temperature	Y8	Material temperature before welding (preheat) that is not in accordance with the procedure can cause defects in the weld.	120.00

The Risk Priority Number (RPN) value for FCAW-GS welding at the Y joint (Table 10) shows the highest result at the risk of insufficient cleanliness between welding seams with an RPN value of 264.44, while the lowest value is at the risk of a machine that is not functioning properly with an RPN value of 59.11.

Risk Classification.

The risk classification with the highest RPN (Risk Priority Number) value indicates the most serious potential hazard in a process, based on a combination of severity, likelihood of occurrence, and detectability. Risks with the highest RPN from each connection must be the top priority to be addressed because they have the potential to cause the greatest loss or the most significant disruption to the quality of the welding results. Here are the highest RPN values of the T, K, and Y joints:

TABEL 11.
THE HIGHEST RPN VALUE OF FCAW-GS WELDING RISK IN T, K & Y JOINTS

No.	Criteria Risk	Risk Event	Code	Risk Agent	RPN
1	Environmental Risks	Preheat Temperature	T8	Inadequate material temperature before welding (preheat) can cause weld defects	158.33
2	Technical Risk	Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	308.00
3	Technical Risk	Inter-pass cleanliness	Y4	Poor cleanliness between weld layer can lead to contamination or defects in the resulting joint.	264.44

Risk Mitigation Strategy Based on Highest RPN After mapping the risks and obtaining the Risk Priority Number (RPN) value, as well as mapping based on the severity (impact) and occurrence (possibility) values, the next step is to develop a mitigation strategy to prevent the recurrence of these risks (Table 12).

TABLE 12.
MITIGATION STRATEGY RESULTS

No.	Code	Risk Agent	Mitigation measure
	T Joint		
1	T9	Inadequate material temperature before welding (preheat) can cause weld defects.	Inspector do inspection before root weld starts and Training of Welders and Fitters on the Importance of Preheat
	K Joint		
2	K5	Lack of cleanliness between weld layer can cause contamination or defects in the joint.	Establish a mandatory procedure for cleaning between layers using steel wire brushes, chipping hammers and grinders (if slag is thick or adherent) and cleaning is carried out before each subsequent pass begins.
	Y Joint		
3	Y4	Lack of cleanliness between weld layer can cause contamination or defects in the joint.	Establish a mandatory procedure for cleaning between layers using steel wire brushes, chipping hammers and grinders (if slag is thick or adherent). Cleaning is carried out before each subsequent pass begins.

Evaluation of the Effectiveness of FMEA Implementation

The welding quality evaluation results showed that out of 998 T-K-Y joints, only 12 joints were rejected, equivalent to 1.2%. This is very low, especially in the context of a large-scale, highly complex marine construction project such as an offshore wind farm.

This achievement indicates that:

- The risk management system in place has functioned effectively in mitigating the key risks of weld failure.
- The critical risks such as inadequate preheating and poor inter-pass cleanliness, have been identified and controlled through targeted supervision and training strategies.
- The previously high RPN value was successfully lowered implicitly, indicated by the low number of actual failures that occurred.

IV. CONCLUSION

This study successfully identified, analysed, and mitigated the key risks in FCAW-GS welding on T-K-Y joints in offshore wind farm jacket construction using the Failure Mode and Effect Analysis (FMEA) method. The highest-priority risk factors identified based on Risk Priority Number (RPN) analysis are:

- In T joints, inadequate material temperature before welding (preheat) resulted in the highest RPN value of 158.33.
- In K joints, poor cleanliness between weld seams posed the greatest risk, with an RPN of 308.00.
- In Y joints, similar cleanliness deficiencies also emerged as the dominant risk, with an RPN of 264.44.

Through structured FMEA-based risk prioritization and mitigation strategies such as pre-weld inspections, mandatory inter-pass cleaning, and targeted training the number of rejected joints was minimized to 12 out of 998, equivalent to a rejection rate of only 1.2%.

This outcome demonstrates that:

- Risk management implemented in accordance with ISO 31000:2018 was effective not only in responding to failures but also in proactively preventing them.
- The FMEA method proved to be a reliable tool for quantifying and addressing welding risks through realistic and specific failure mode mapping.
- The integration of quantitative risk analysis into welding for offshore structural can significantly

enhance process quality, reduce rework, and improve reliability.

Hence, this study contributes a validated framework for structured risk management in offshore structural welding, supporting both quality assurance and project efficiency in critical infrastructure.

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