International Journal of Marine Engineering Innovation and Research, Vol. 11(2), Jun. 2026. 487-496
(pISSN: 2541-5972, eISSN: 2548-1479)

Root Cause Analysis of Compression-bar Failure on Manual Pontoon Hatch Cover Systems

Arwen Surya A. A[1], Aulia Widyandari [2], Zulfaidah Ariany [3] , Mohd. Ridwan[4], Tuti Rachmawati Y[5*]

(Received: 11 February 2026 / Revised: 13 February 2026 / Accepted: 19 February 2026 / Available Online: 8 June 2026)

Abstract**—** Hatch covers are critical for maintaining cargo hold watertight integrity. In manual pontoon-type systems, compression bar geometry directly governs rubber packing pressure and sealing performance. A practical problem was identified in a newly constructed Gearless Multi-Purpose Vessel at PT. KTU Shipyard, where several hatch covers exhibited marginal ultrasonic leakage indications despite meeting dimensional tolerances. This condition highlights a gap between geometric compliance and actual functional sealing performance. This study aims to evaluate the as-built compression bar condition and to identify the systemic root causes of marginal sealing performance using Root Cause Analysis (RCA). A descriptive–analytical case study was conducted through visual inspection, dimensional measurement within a 14–24 mm tolerance range, ultrasonic testing with an acceptance limit of <10% OHV, and technical document review. Data were analyzed using correlation assessment, fishbone diagrams, and 5 Why's analysis. Although all compression bars were dimensionally compliant, marginal ultrasonic readings (1–2 dB; 2–4% OH) indicated reduced sealing safety margins. The novelty of this study lies in integrating dimensional compliance with functional leakage indicators to identify systemic fabrication and inspection deficiencies. Results show that process-related factors, rather than material failure, are the dominant causes, highlighting the need for condition-based quality control.

Keywords— Compression Bar, Hatch Cover, Root Cause Analysis (RCA), MPV Gearless, Ship Construction.

Corresponding Author: tuti.yusuf@ktushipyard.com

I. INTRODUCTION

Hatch covers are essential structural components that maintain cargo hold watertight integrity and protect cargo from seawater ingress and environmental exposure during operation [1]. On Multipurpose Vessels (MPVs), particularly gearless types, manual pontoon hatch covers are widely applied because of their simple operating mechanism and adaptability to different cargo arrangements [2]. In service, these covers function not only as protective closures but also as temporary working platforms during loading and unloading, making both structural reliability and sealing effectiveness operationally critical [3].

For pontoon-type hatch covers, sealing performance largely depends on the dimensional consistency of the compression bar, which regulates contact pressure between the hatch panel and the rubber packing along the coaming [4]. In practice, minor geometric deviations may occur due to welding heat input, plate distortion, fabrication tolerances, or alignment inconsistencies during installation [5]. While each deviation may remain within allowable limits, their combined influence can disturb pressure uniformity along the sealing line, particularly in long hatch openings where small irregularities accumulate [6].

Field inspection records show that slight leakage indications may still appear even when hose and ultrasonic tests meet formal acceptance criteria [7]. This suggests that compliance with dimensional tolerances and PASS/FAIL inspection standards does not necessarily represent actual sealing behaviour under service conditions. Although previous studies emphasize fabrication control and inspection procedures [9], limited attention has been given to the interaction between marginal geometric deviations and measurable leakage responses in as-built structures.

Accordingly, this study examines the relationship between compression bar geometric conformity and ultrasonic leakage performance using a structured Root Cause Analysis (RCA) approach [11]. Dimensional and leakage data are evaluated together to obtain a more functional interpretation of sealing behaviour. The results indicate that meeting tolerance requirements alone does not guarantee uniform sealing pressure along the hatch perimeter. Instead, marginal leakage tendencies are primarily associated with cumulative fabrication and installation variations rather than material degradation. These findings support the development of a performance-oriented evaluation framework to complement conventional compliance checks and strengthen fabrication control in shipbuilding practice [14].

II. METHOD

A. Research Research Design and Object

This study employs a descriptive analytical approach supported by Root Cause Analysis (RCA) to examine non-conformities identified in the compression

Arwen Surya Adi Anjalu with Department of Engineering Technology, Universitas Diponegoro, Semarang, 50275, Indonesia. E-mail: arwensurya220704@gmail.com

Aulia Widyandari with Department of Engineering Technology, Universitas Diponegoro, Semarang, 50275, Indonesia. E-mail:auliawindyandari@lecturer.undip.ac.id

Zulfaidah Ariany with Department of Engineering Technology, Universitas Diponegoro, Semarang, 50275, Indonesia. E-mail:zariany@live.undip.ac.id

Mohd. Ridwan with Department of Engineering Technology, Universitas Diponegoro, Semarang, 50275, Indonesia. E-mail:mohdridwan@lecturer.undip.ac.id

Tuti Rachmawati Yusufwith Departement of Production, PT. KTU Shipyard Tanjung Riau, Batam, 29425, Indonesia. E-mail: tuti.yusuf@ktushipyard.com

bar system of a manual pontoon-type hatch cover installed on a Gearless Multi-Purpose Vessel (MPV) [15]. The object of this research is the compression bar assembly installed on a Gearless MPV constructed at PT. KTU Shipyard. The investigation focuses on the actual as-built condition, particularly fabrication quality and installation accuracy, as observed directly in the field and verified through shipyard technical documentation [16].

B. Data Collection and Inspection Methods

Data were gathered through field inspection and review of relevant technical documents. The evaluation consisted of visual examination, dimensional measurement, and ultrasonic tightness testing, which are commonly applied in hatch cover condition assessment [17]. Visual inspection was conducted to identify surface imperfections, local deformation, misalignment, corrosion, and welding irregularities affecting the compression bar [18]. Dimensional measurements were performed using calibrated measuring instruments to assess compression bar height, surface flatness, and rubber packing compression, ensuring accuracy and repeatability [19]. Ultrasonic testing was carried out to evaluate hatch cover weathertight performance by detecting potential leakage paths along the hatch perimeter and cross joints under fully closed conditions [20]. Additionally, ship drawings, fabrication records, and installation procedures were reviewed to confirm conformity with approved design specifications and shipyard practices [21].

C. Data Reference Standards and Root Cause Analysis Method

Inspection results were evaluated with reference to manufacturer guidelines issued by MacGregor and classification requirements established by ClassNK [22]. Tolerance limits for compression bar geometry and rubber packing compression were used as benchmarks to determine technical conformity [23]. To identify the underlying causes of detected deviations, Root Cause Analysis (RCA) was applied as a structured analytical method [24]. The process included problem identification, validation of field data, categorization of observed conditions, and systematic evaluation of potential contributing factors related to fabrication methods, installation practices, workmanship consistency, and inspection procedures [25].

D. Data Analysis Procedure

The measured data is evaluated based on valid reference standards to determine the level of compatibility of the compression bar system [26]. The identified deviations are then analyzed for their potential impact on sealing performance and operational safety. Results from visual inspection, dimensional measurement, and ultrasonic testing are then integrated into the RCA framework to identify root causes and support the formulation of valid technical conclusions and recommendation for improvement [27].

III. Results and Discussion

A. Field Data Classification

Field data classification was performed to systematically organize raw inspection data based on testing methods and observed conditions.

1. Visual inspection

Data were obtained through direct on-site inspection of the manual pontoon-type hatch covers to evaluate surface wear, corrosion, localized deformation, surface irregularities, and welding defects that could potentially affect sealing performance. The identified conditions are categorized based on their severity to enable structured analysis and ensure accurate interpretation of the overall structural integrity and sealing performance of the hatch covers.

Table 1.
Visual Test Data

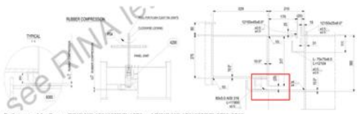
Hatch Cover	Surface Wear	Corrosion	Local Deformation	Surface Irregularities	Welding Defects	Visual Category	Location of Findings
01	Not	Not	Not	Flat	Not	Good	Along the Side
02	Not	Not	Not	Flat	Not	Good	Along the Side
03	Not	Not	Not	Flat	Not	Good	Along the Side
04	Not	Not	Not	Flat	Not	Good	Along the Side
05	Middle	Not	Not	Not Flat	Grinding Marks	Middle	Center of the Port
06	Not	Not	Not	Flat	Not	Good	Along the Side
07	Middle	Not	Not	Not Flat	Middle Overlap	Middle	Panel Corner
08	Not	Not	Not	Flat	Nothing	Good	Along the Side
09	Not	Not	Not	Flat	Nothing	Good	Along the Side
10	Middle	Middle	Middle	Not Completely Flat	Local Undercut	Pretty Bad	Starboard Side
11	Middle	Not	Not	Not Flat	Small Porosity	Middle	Middle Panel

2. Manual Measurement Data

Measurements were conducted at approximately one-meter intervals to obtain a representative profile of the compression bar height distribution. The data presented correspond to MPV Gearless 1387 and reflect the actual as-built condition of the compression bar along its full longitudinal extent. The selected measurement spacing was intended to capture potential localized geometric variations arising from fabrication activities, welding-induced distortion, or alignment inconsistencies during installation—conditions that may not be detected through limited sampling points. Such localized deviations are technically significant, as even minor variations in height or flatness can affect the uniformity of rubber packing compression and, consequently, influence the overall weathertight performance of the hatch cover system. Therefore, the dimensional measurement results provide a quantitative foundation for evaluating geometric conformity, correlating irregularities with sealing performance, and supporting the subsequent compliance assessment and Root Cause Analysis (RCA).

TABLE 2.
MANUAL MEASUREMENT DATA

COMPRESSION BAR		
PROJECT KTU - 1387		
PORT	FWD	STBD



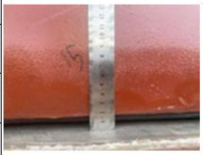
References : MacGregor DWG NO 1281032WD-1270 and DWG NO 1281032WD-2700-2710

17 mm	19 mm	24 mm	24 mm	24 mm	22 mm	24 mm	20 mm	15 mm	15 mm

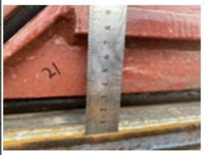

PORT	HC No.1	STBD
19 mm		19 mm
22 mm		23 mm
22 mm		22 mm
17 mm		21 mm


PORT	HC No.2	STBD
20 mm		19 mm
20 mm		15 mm
20 mm		18 mm
19 mm		20 mm

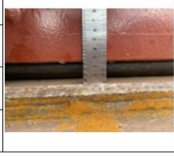

PORT	HC No.3	STBD
18 mm		19 mm
17 mm		14 mm
20 mm		15 mm
20 mm		20 mm




PORT	HC No.4	STBD
22 mm		20 mm
17 mm		19 mm
15 mm		19 mm
18 mm		22 mm

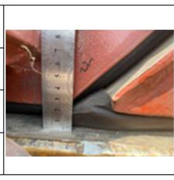



PORT	HC No.5	STBD
21 mm		19 mm
20 mm		20 mm
19 mm		20 mm
20 mm		20 mm

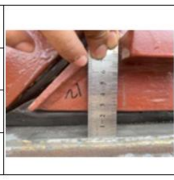



PORT	HC No.6	STBD
24 mm		20 mm
19 mm		16 mm
19 mm		18 mm
24 mm		21 mm

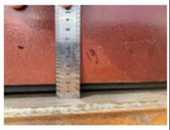

PORT	HC No.7	STBD
19 mm		20 mm
19 mm		19 mm
17 mm		18 mm
19 mm		19 mm



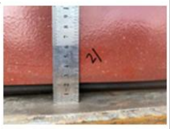

PORT	HC No.8	STBD
22 mm		19 mm
19 mm		19 mm
18 mm		17 mm
23 mm		19 mm




PORT	HC No.9	STBD
20 mm		19 mm
19 mm		23 mm
21 mm		22 mm
21 mm		21 mm

PORT	HC No.10	STBD
23 mm		19 mm
20 mm		17 mm
20 mm		19 mm
21 mm		20 mm

PORT	HC No.11	STBD
22 mm		20 mm
19 mm		20 mm
19 mm		21 mm
21 mm		19 mm

23 mm	24 mm	24 mm	23 mm	24 mm	24 mm	23 mm	24 mm	21 mm	21 mm

3. Ultrasonic Test Data

The ultrasonic testing procedure requires careful execution, involving the placement of a transmitter inside the cargo hold to generate ultrasonic signals, which are subsequently detected by a portable receiver operated along the hatch cover perimeter and cross joints. The data presented correspond to MPV Gearless 1387 and were collected with the hatch cover fully closed and properly secured to simulate actual operational sealing conditions.

This method enables sensitive detection of potential leakage paths by identifying ultrasonic signal transmission through small gaps between the hatch cover and the coaming. Differences in recorded signal intensity indicate variations in local sealing effectiveness, which may be influenced by compression bar geometry, rubber packing condition, and the distribution of contact pressure. The results of the ultrasonic test are used to supplement visual inspections and dimensional measurements by providing functional verification of watertight performance. These test results also help to identify specific areas that require further evaluation in additional analyses.

TABLE 3.
ULTRASONIC TEST DATA

No.	Hatch No	Location	Leaky Seal	Leak Type	Measurements With Closed Hatch			Test Result		dB Reading after corrective action	Remark
					dB	OH	OHV Cal or dB Ref	PASS	FAIL		
1	HC. 1	1	-	-	0	0%	58	PASS	-	-	TEST PASSED
2	HC. 2	2	-	-	0	0%	58	PASS	-	-	TEST PASSED
3	HC. 3	3	-	-	0	0%	58	PASS	-	-	TEST PASSED
4	HC. 4	4	-	-	0	0%	58	PASS	-	-	TEST PASSED
5	HC. 5	5	-	-	1	2%	58	PASS	-	-	TEST PASSED
6	HC. 6	6	-	-	0	0%	58	PASS	-	-	TEST PASSED
7	HC. 7	7	-	-	1	2%	58	PASS	-	-	TEST PASSED
8	HC. 8	8	-	-	0	0%	58	PASS	-	-	TEST PASSED
9	HC. 9	9	-	-	0	0%	58	PASS	-	-	TEST PASSED
10	HC. 10	10	-	-	2	4%	58	PASS	-	-	TEST PASSED
11	HC. 11	11	-	-	1	2%	58	PASS	-	-	TEST PASSED

During visual inspection, no significant structural defects, major deformations, or material damage were found. The compression bar segments, however, showed minor welding imperfections and slight misalignment. Although these findings are still within acceptable construction appearance standards, local geometric variations would affect the even loading distribution when the hatch cover is in the closed position. A relatively small variation in alignment along the length of the hatch cover could cause uneven load transfer between the compression bar and the rubber packing. Therefore, although visually acceptable, this condition needs to be further evaluated for its impact on sealing performance.

Limited to assessing visible surface conditions, visual inspection alone cannot fully represent the functional performance of the sealing interface, as it does not capture the actual pressure distribution during operational closure. Minor geometric variations that seem insignificant during visual examination may still alter the contact interaction between the compression bar and the rubber packing once the hatch cover is secured.

Accumulating along extended hatch configurations, such localized inconsistencies can gradually reduce overall compression uniformity. Therefore, visual findings should be interpreted together with dimensional measurements and ultrasonic test results to obtain a more comprehensive evaluation of sealing performance.

B. Technical Compliance Analysis

Compliance analysis is conducted by comparing measurement and test results against applicable technical standards without considering causal factors. Based on visual inspection results, manual compression bar measurements, and ultrasonic tests, the collected data are classified into three condition categories as shown in the following table. This classification is intended to objectively assess the level of conformity of the compression bar system with the specified geometric tolerances, surface condition, and weathertight performance. The categorization provides a clear distinction between fully compliant conditions, marginal conditions approaching tolerance limits, and non-compliant conditions exceeding allowable thresholds. By applying this structured classification, the compliance analysis establishes a factual baseline of the as-built condition, which is essential for identifying critical areas requiring further investigation and for supporting subsequent analytical stages.

TABLE 4.
GENERAL CRITERIA CATEGORY

Category	General Criteria	Technical Reference
Normal	All construction parameters and inspection results are within the required tolerance limits, and the leak test results show that the product has passed without any indication of leakage.	ClassNK (2024); MacGregor (2022)
Marginal	Construction parameters are still within tolerance limits, but are approaching minimum or maximum values, and/or show indications of low leakage in ultrasonic test results.	MacGregor (2022); ClassNK (2024)
Not Suitable	The construction parameters are outside the specified tolerance limits and/or the leak test results indicate failure.	ClassNK (2024); MacGregor (2022)

This categorization integrates visual inspection results, manual compression bar measurements, and ultrasonic test data to provide an objective assessment of conformity with specified technical tolerances. The Normal category indicates full compatibility, where all parameters are within the specified limits and ultrasonic testing confirms effective waterproof performance. The Marginal category represents conditions that remain within tolerance limits but are approaching critical thresholds, potentially reducing sealing reliability over time. The Not Suitable category identifies conditions that exceed tolerance limits and/or show clear indications of leakage, indicating functional non-compliance. Overall, this classification provides a clear base for existing conditions and supports consistent evaluation prior to further analysis.

TABLE 5.
TECHNICAL CRITERIA ACCORDING TO MACGREGOR

Category	General Criteria
Normal	Value is within tolerance
Margin	Value is close to 14 mm or 24 mm
Not Suitable	Outside tolerance

The ultrasonic measurement is used to evaluate the performance of the hatch cover sealing system by identifying indications of leakage in the form of dB values and over-hear (OH) percentages. These parameters provide functional confirmation of sealing effectiveness and are used to correlate dimensional compliance with actual weathertight performance, as described in the table below.

TABLE 6.
TECHNICAL CRITERIA ACCORDING TO CLASSNK

Category	UT Result
Normal	PASS, dB = 0
Margin	PASS, dB > 0
Not Suitable	FAIL

Visual inspection, manual compression bar measurements, and ultrasonic test results were integrated to assess the overall condition of the hatch cover. Visual data represent physical condition and workmanship quality, dimensional measurements indicate compliance with technical tolerances, and ultrasonic testing reflects sealing performance. Based on this integration, hatch cover conditions were classified as normal, marginal, or non-compliant, which served as the basis for prioritizing objects for further Root Cause Analysis (RCA), particularly those in marginal and non-compliant conditions, as summarized in the table below.

TABLE 7.
DATA INTEGRATION RESULT

Hatch Cover	Compression Bar Condition	Tolerance Compliance (14-24 mm)	UT Result (dB)	OH (%)	Status UT	Visual	Condition Category
HC 1	There are some parts that are close to the lower and upper limits, but the rest are within limits.	Fulfill	0	0%	PASS	Good	Normal
HC 2	There is one point that is close to the lower limit, but the rest are within limits.	Fulfill	0	0%	PASS	Good	Normal
HC 3	There are some parts that are close to the lower limit, but the rest are within limits.	Fulfill	0	0%	PASS	Good	Normal

CONTINUED TABLE 7.
DATA INTEGRATION RESULT

HC 4	There are some parts that are close to the lower limit, but the rest are within limits.	Fulfill	0	0%	PASS	Good	Normal
HC 5	Overall, it is safe and within limits.	Fulfill	1	2%	PASS	Middle	Marginal
HC 6	There are several parts that almost touch the upper limit, but the rest are in order.	Fulfill	0	0%	PASS	Good	Normal
HC 7	Overall, it is in safe and proper condition.	Fulfill	1	2%	PASS	Middle	Marginal
HC 8	There are several parts that almost touch the upper limit, but the rest are in order.	Fulfill	0	0%	PASS	Good	Normal
HC 9	There are several parts that almost touch the upper limit, but the rest are in order.	Fulfill	0	0%	PASS	Good	Normal
HC 10	There are several parts that almost touch the upper limit, but the rest are in order.	Fulfill	2	4%	PASS	Pretty Bad	Marginal
HC 11	There are several parts that almost touch the upper limit, but the rest are in order.	Fulfill	1	2%	PASS	Middle	Marginal

Based on the table, all compression bar heights fall within the technical tolerance range of 14–24 mm and are therefore dimensionally compliant with manufacturer standards. However, ultrasonic test results indicate variations in dB and OH (%) values on several hatch covers (HC.5, HC.7, HC.10, and HC.11) which, although classified as PASS, suggest low-level leakage. These conditions are categorized as marginal, indicating that despite dimensional compliance, uneven pressure distribution or surface conditions may affect sealing performance, thereby justifying further analysis using the Root Cause Analysis (RCA) method.

The ultrasonic test results remain below the acceptance threshold of 10% OHV, indicating that the hatch covers are technically weathertight. However, marginal readings in the range of 1–2 dB (2–4% OH) suggest a reduced sealing safety margin at specific locations. While these values do not represent failure, they may indicate localized pressure non-uniformity. Under operational conditions involving cyclic loading, hull deflection, or long-term service exposure, such marginal indications could potentially develop into measurable leakage. Therefore, the ultrasonic findings provide functional insight beyond simple pass–fail classification.

C. Data correlation analysis

Data correlation analysis was conducted to relate compression bar physical conditions to hatch cover sealing performance prior to Root Cause Analysis (RCA). Visual inspection findings, dimensional measurement results, and ultrasonic tightness test data were systematically correlated to identify initial cause–effect relationships between construction deviations and sealing effectiveness. This correlation process enabled the identification of recurring patterns, such as the association between local surface irregularities, uneven rubber packing compression, and detected leakage indications. The results of this preliminary analysis were used to refine the RCA process by focusing the investigation on dominant variables that directly influence hatch cover watertight integrity and operational reliability.

1. Surface Condition and Ultrasonic Test Results

Uneven compression bar surfaces identified during visual inspection correlated with higher dB and OH (%) values in ultrasonic testing compared to smooth surfaces, indicating reduced sealing performance, as shown in the data below.

TABLE 8.
SURFACE CONDITION AND ULTRASONIC TEST RESULTS

Hatch Cover	Visual Condition	Hasil UT (dB)	OH (%)	Category
HC.5	Middle	1	2%	Marginal
HC.7	Middle	1	2%	Marginal
HC.1	Good	0	0%	Normal

The data shows that the irregularity of the compression bar surface affects the effectiveness of contact between the compression bar and the rubber packing, thereby reducing the quality of the seal even though it is still within acceptable limits.

2. Compression Bar Height and Rubber Pressure Distribution

Manual measurements revealed minor variations in compression bar height, although still within the 14–24 mm tolerance range. These variations may cause uneven pressure distribution on the rubber seal along the hatch coaming, as shown in the data below.

TABLE 9.
COMPRESSION BAR HEIGHT AND RUBBER PRESSURE DISTRIBUTION

Hatch Cover	Compression Bar Condition	Compression Bar Value Range	UT Result (dB)	Category
HC.10	There are some parts that are close to the upper limit, but the rest are within the limits.	Varied	2	Marginal
HC.5	Overall, it is in safe and proper condition.	Overall Same	1	Marginal
HC.6	There are some parts that are close to the upper limit, but the rest are within the limits.	Varied	0	Normal

3. Misalignment and Increased Leakage Indicators

Visual inspection identified slight misalignment of several compression bar segments relative to the hatch coaming, which correlated with increased dB and OH (%) values in ultrasonic testing, although the results remained within PASS criteria, as shown in the data below.

TABLE 10.
MISALIGNMENT AND INCREASED LEAKAGE INDICATORS

Hatch Cover	Misalignment Findings	OH (%)	UT Status	Category
HC.10	Minor	4%	PASS	Marginal
HC.11	Minor	2%	PASS	Marginal
HC.2	Not	0%	PASS	Normal

Integration of visual inspection, compression bar measurements, and ultrasonic test results shows that localized surface irregularities, dimensional variations near tolerance limits, and slight misalignment correlate with low-level leakage and marginal sealing performance. Although all results remain within acceptance criteria, these deviations reduce the sealing safety margin and therefore serve as key indicators for further Root Cause Analysis (RCA).

The ultrasonic test results remain below the acceptance threshold of 10% OHV, indicating that the hatch covers are technically weathertight. However, marginal readings in the range of 1–2 dB (2–4% OH) suggest a reduced sealing safety margin at specific locations. While these values do not represent failure, they may indicate localized pressure non-uniformity. Under operational conditions involving cyclic loading, hull deflection, or long-term service exposure, such marginal indications could potentially develop into measurable leakage. Therefore, the ultrasonic findings provide functional insight beyond simple pass–fail classification.

D. Root Cause Analysis (RCA)

Root Cause Analysis (RCA) was applied to non-compliant and marginal data identified during compliance and correlation analyses, including uneven compression bar surfaces, thickness variations near tolerance limits, and slight misalignment affecting ultrasonic test results. This stage aimed to systematically identify the root causes of actual or potential sealing failures in pontoon-type manual hatch covers, considering both component conditions and process-related factors.

1. Cause Effect Diagram (Fishbone)

A cause–effect diagram was used as the initial RCA tool to systematically map the relationship between the main problem and its contributing factors. The primary effect was defined as non-uniform compression bar geometry that reduces the hatch cover sealing margin, as indicated by marginal and non-compliant inspection results. Based on field data, potential causes were grouped into six categories: human factors related to skill consistency and tolerance interpretation; work methods lacking standardized welding, surface finishing, and post-weld control procedures; equipment limitations affecting surface flatness and measurement accuracy; material variability influencing welding distortion; measurement practices focused mainly on PASS/FAIL UT results without detailed marginal analysis; and environmental conditions in open fabrication areas that constrained welding and installation quality.

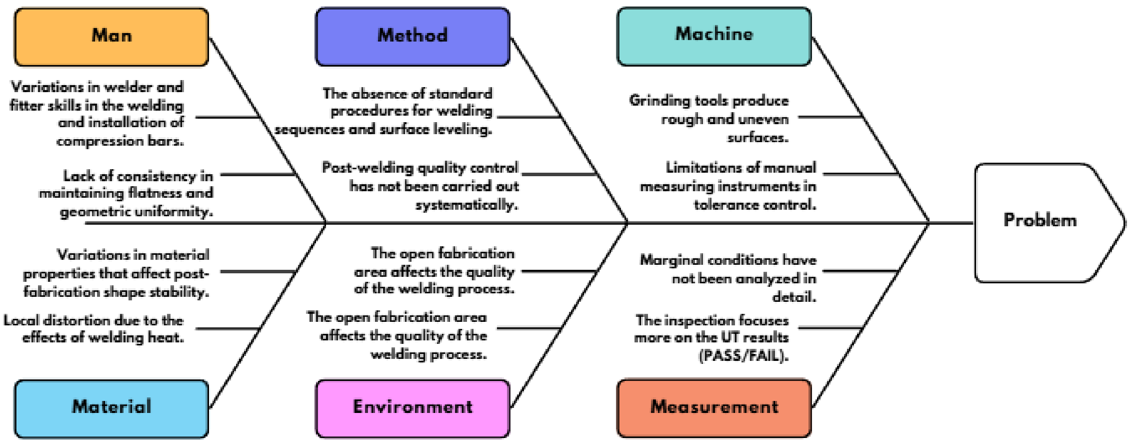


Figure. 1. Fishbone Diagram.

The fishbone analysis indicates that compression bar non-conformities in pontoon-type hatch covers result from a combination of work methods, human skills, and inspection practices rather than a single factor. The absence of standardized procedures and skill variability leads to inconsistent fabrication, while inspection systems focused on final results fail to detect marginal conditions early, indicating a systemic, process-related issue requiring integrated improvements from fabrication to inspection.

2. Dominant Cause Validation

The validation of the root causes is made after the fishbone analysis to ensure that the factors selected for deeper investigation are directly supported by the field data. Potential causes identified across human, method, equipment, material, measurement, and environmental aspects were evaluated against visual inspection findings, manual compression bar measurements, and ultrasonic test results. Only causes showing consistent and direct correlation with marginal and non-compliant conditions were retained as dominant causes, while unsupported factors were excluded, as summarized in the table below

TABLE 11.
DOMINANT CAUSE VALIDATION

Dominant type of Cause	Causative Factor	Field Evidence	Technical Impact	Category
Material–Process	Local distortion due to welding heat	The compression bar surface was found to be uneven and the flattening marks were not uniform on HC.5 and HC.7.	The contact compression bar–rubber is uneven.	Marginal
Method	No standard welding sequence and flattening procedures	Variations in finishing quality between hatch covers despite being within dimensional tolerances.	The rubber pressure distribution is not uniform.	Marginal
Measurement	Inspection focused on UT results (PASS/FAIL)	Low leakage values (1–2 dB; OH 2–4%) were still declared PASS.	Marginal conditions are not detected early.	Marginal not Suitable

The validation results narrowed the analysis from all fishbone branches to three dominant causes related to material–process interactions, work methods, and measurement/inspection practices. These dominant causes were further examined using the 5 Why's Analysis to systematically identify the root causes**.**

3. Analysis 5 Why's

After dominant causes were validated using fishbone analysis and field data, a 5 Why's Analysis was conducted to sequentially trace cause–effect relationships from observed symptoms to the root causes. This analysis aimed to demonstrate that marginal compression bar conditions—characterized by uneven surfaces, dimensional variability, and low-level leakage in ultrasonic testing—stem from deficiencies in fabrication processes, work methods, and inspection systems rather than isolated component failures, as summarized in the table below.

TABLE 12.
ANALYSIS 5 WHY'S

Why Stage	Why Question	Answers Based on Field Data	Correlation with Dominant Causes
Why 1	Why is the compression bar in marginal condition and showing slight leakage?	Because the pressure between the compression bar and the rubber seal is unequal at some points.	Direct impact on sound insulation performance (UT 1–2 dB; OH 2–4%).
Why 2	Why is the rubber seal pressure uneven?	Because the thickness and flatness of the compression bar surface varied along the panel.	Consistent with findings of thickness variations and uneven surfaces.
Why 3	Why do the thickness and flatness of the compression bar vary?	Because local distortion occurs due to welding heat and an uneven flattening process.	Dominant cause: Material–Process type.
Why 4	Why is the surface leveling process not performed consistently?	Because there is no standard procedure governing the welding sequence and finishing method.	Dominant cause: Method type.
Why 5	Why are these standard procedures not available and implemented?	Because the inspection system focuses more on the final ultrasonic test results (PASS/FAIL) without marginal condition criteria.	Dominant cause: Measurement type.

Based on the 5 Why's analysis, the primary root cause of marginal compression bar conditions in pontoon-type hatch covers is the absence of an integrated fabrication and inspection procedure to control surface flatness and geometric tolerances, allowing marginal conditions to pass without corrective action.

4. Determination of Root Cause

The 5 Whys analysis shows that the marginal conditions observed on the pontoon-type hole cover compression bar were not caused by material defects or structural defects, but instead by weaknesses in work methods and quality control practices. Although the material met specifications and most ultrasonic test results were categorized as PASS, field data revealed uneven surface conditions, thickness variations close to tolerance limits, and low-level leakage. These findings point to weaknesses in the fabrication process and inspection practices. The absence of integrated standard procedures to regulate the welding sequence, surface finishing, and post-weld acceptance—combined with an inspection system that focused only on PASS/FAIL ultrasonic results without recognizing marginal conditions—allowed these deviations to continue. The result was that the root causes were identified in the methods and measurements, forming the basis for developing improved fabrication and inspection procedures to enhance hatch cover sealing reliability. A comparison between dimensional measurements and ultrasonic responses further indicated that geometric match alone does not fully explain sealing performance behavior. Although all compression values are within the specified tolerance range, marginal ultrasonic indications are also identified. This confirms the presence of a functional discrepancy between dimensional conformity and actual sealing response. The findings highlight that tolerance-based inspection, when applied independently, may not adequately reflect real sealing performance. A more integrative approach to evaluation is therefore needed to interpret the effectiveness of compression rods in an operational context.

E. Preparation of Technical Recommendations

Based on fishbone analysis, root cause validation, and 5 Whys analysis, the problems observed in pontoon-type hatch cover compression rods were not only caused by component conditions, but mainly by weaknesses in work methods and inspection systems. Therefore, targeted technical recommendations were developed to directly address the root causes of this problem, using field evidence and its impact on sealing performance as a basis, as systematically described in the table below.

TABLE 13.
PREPARATION OF TECHNICAL RECOMMENDATONS

No	Root Cause	Supporting Data Evidence	Impact on Hatch Cover	Technical Recommendations
1	Lack of integrated standard procedures for compression bar fabrication.	Variations in flatness and thickness of compression bars; uneven surfaces on some hatch covers.	Uneven rubber seal pressure; marginal UT results	Develop and implement SOPs for compression bar fabrication that cover welding sequences, surface leveling methods, and internal work tolerance limits
2	Post-welding surface leveling process is not standardized.	Rough grinding marks and local irregularities on the surface of compression bars.	Decreased compression bar–rubber seal contact quality	Establish standard finishing methods and surface flatness criteria prior to hatch cover installation
3	Inspection system only focuses on final UT results (PASS/FAIL).	Marginal conditions (1–2 dB; OH 2–4%) still passed.	Potential failure not detected early	Develop additional inspection criteria for marginal conditions and integrate visual, measurement, and UT results
4	Lack of follow-up limits for marginal conditions.	No repairs were made despite minor deviations being found.	Decreased system tightness safety margin	Establish specific corrective action procedures for marginal conditions before hatch covers are declared acceptable
5	Lack of quality control during the fabrication process.	Variations in results between hatch covers despite identical designs.	Product quality inconsistency	Implement step-by-step quality control (in-process inspection) during compression bar fabrication

This table shows that the technical recommendations formulated from the identified root causes through a systematic Root Cause Analysis (RCA) process. Each recommendation is directly linked to the supporting data evidence and the observed impact on hatch cover performance, ensuring a clear relationship between field findings and corrective actions. The identified root causes mainly relate to inconsistencies in fabrication procedures, surface leveling practices, inspection focus, and quality control, which collectively influence compression bar geometry and sealing effectiveness.

The recommended actions focus on strengthening fabrication and inspection controls through more standardized procedures. This includes ensuring proper surface finishing practices, applying inspection criteria based on actual conditions, and establishing clear acceptance and correction limits for parts that are close to tolerance limits. By integrating these measures into fabrication and installation processes, the recommendations aim to improve dimensional consistency, enhance system tightness, and reduce the risk of future sealing failures in manual pontoon-type hatch cover systems.

The Root Cause Analysis indicates that the dominant contributing factors are related to fabrication sequencing, welding heat control, alignment accuracy during installation, and inspection practices focused primarily on final acceptance criteria. There is no data to indicate that material degradation or rubber seal failure is the primary cause. This confirms that the marginal leakage tendencies observed are systemic and process-related rather than component-based failures. The findings emphasize the importance of process-oriented quality control and performance-based inspection strategies in ensuring long-term sealing reliability of hatch cover systems.

IV. CONCLUSION

This study was undertaken to address a critical gap in hatch cover construction assessment, specifically the prevailing assumption that dimensional compliance inherently guarantees sealing reliability. In current shipyard practice, evaluation procedures predominantly emphasize geometric tolerance verification and binary PASS/FAIL ultrasonic acceptance criteria. Such approaches, however, are insufficient to detect marginal conditions that may progressively compromise sealing performance and reduce operational safety margins.

The findings demonstrate that all compression bars satisfied the specified dimensional tolerance range of 14–24 mm and fulfilled ultrasonic acceptance requirements (<10% OHV). Despite this formal compliance, several hatch covers exhibited marginal ultrasonic readings (1–2 dB; 2–4% OH), which were consistently correlated with localized surface irregularities, welding-induced distortion, and minor installation misalignment. These results clearly indicate that geometric conformity alone does not reliably represent functional sealing integrity.

The principal contribution of this research lies in the systematic integration of dimensional compliance assessment with functional leakage indicators within a structured Root Cause Analysis (RCA) framework. Based on correlation analysis, fishbone mapping, and 5 Whys validation, this study concluded that marginal seal degradation was primarily caused by systemic process deficiencies. The study identified non-standardized welding sequences, inconsistent surface finish control, and an inspection system limited to binary acceptance criteria without clear thresholds for marginal conditions.

Accordingly, this research advances a performance-oriented evaluation paradigm that redefines hatch cover quality assurance from tolerance-based verification toward condition-based reliability assessment. The proposed framework provides both theoretical and practical contributions for enhancing fabrication control, inspection robustness, and long-term watertight integrity in ship construction projects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge all parties who contributed to this research, including the shipyard for providing access to field inspections, measurement data, and technical documentation.

REFERENCES

[1] International Maritime Organization, International Convention for the Safety of Life at Sea (SOLAS). London, UK: IMO Publishing, 2020.
[2] R. Parulian Sinaga et al., “Operational characteristics of multi-purpose vessels and cargo handling systems,” Journal of Maritime Transportation, vol. 9, no. 2, pp. 45–53, 2015.
[3] The Nautical Institute, Cargo Hatch Covers: Operation, Inspection and Maintenance. London, UK: The Nautical Institute, 2020.
[4] MacGregor, Hatch Cover Systems – Technical Manual. Helsinki, Finland: MacGregor Group, 2020.
[5] ClassNK, Rules for the Survey and Construction of Steel Ships, Part C. Tokyo, Japan: ClassNK, 2024.
[6] ClassNK, Rules for the Survey and Construction of Steel Ships, Part B, Amendment no. 2. Tokyo, Japan: ClassNK, 2023.
[7] MacGregor, Hatch Cover Tightness Testing and Inspection Guidelines. Helsinki, Finland: MacGregor Group, 2022.
[8] Japan P&I Club, Cargo Damage Prevention and Hatch Cover Leakage Risk. Tokyo, Japan: Japan P&I Club, 2022.
[9] J. K. Paik and A. K. Thayamballi, Ship-Shaped Offshore Installations: Design, Building, and Operation. Cambridge, UK: Cambridge University Press, 2019.
[10] PT. KTU Shipyard Tanjung Riau, As-Built Drawings and Fabrication Records of Gearless Multi-Purpose Vessel. Batam, Indonesia: Internal Technical Document, 2024.
[11] J. J. Rooney and L. N. V. Heuvel, “Root cause analysis for beginners,” Quality Progress, vol. 37, no. 7, pp. 45–53, Jul. 2004.
[12] J. Parra Jimenez, “Application of root cause analysis in maritime failure investigation,” International Journal of Maritime Engineering, vol. 158, no. A3, pp. 201–210, 2016.
[13] ClassNK, Guidelines for Ultrasonic Tightness Testing of Hatch Covers. Tokyo, Japan: ClassNK, 2021.
[14] MacGregor, Installation Tolerances and Quality Control for Pontoon Hatch Covers. Helsinki, Finland: MacGregor Group, 2021.
[15] J. W. Creswell, Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, 5th ed. Thousand Oaks, CA, USA: SAGE Publications, 2018.
[16] PT. KTU Shipyard Tanjung Riau, Final Construction Report of Gearless Multi-Purpose Vessel. Batam, Indonesia: Internal Technical Report, 2024.
[17] The Nautical Institute, Guide to Hatch Cover Inspection and Maintenance. London, UK: The Nautical Institute, 2019.
[18] International Association of Classification Societies, Guidelines on Hatch Cover Inspection and Defect Identification. London, UK: IACS, 2020.
[19] International Organization for Standardization, ISO 7500-1: Metallic Materials—Verification of Static Uniaxial Testing Machines. Geneva, Switzerland: ISO, 2018.
[20] Trelleborg Marine Systems, Ultrasonic Hatch Cover Tightness Testing Manual. Stockholm, Sweden: Trelleborg AB, 2021.
[21] PT. KTU Shipyard Tanjung Riau, As-Built Drawings and Installation Records of Hatch Cover System. Batam, Indonesia: Internal Document, 2024.
[22] MacGregor, Hatch Cover Design Criteria and Acceptance Standards. Helsinki, Finland: MacGregor Group, 2021.
[23] ClassNK, Guidelines for Rubber Packing Compression and Hatch Coaming Tolerances. Tokyo, Japan: ClassNK, 2022.
[24] B. Andersen and T. Fagerhaug, Root Cause Analysis: Simplified Tools and Techniques, 2nd ed. Milwaukee, WI, USA: ASQ Quality Press, 2006.
[25] R. K. Mobley, Root Cause Failure Analysis, 2nd ed. Oxford, UK: Butterworth-Heinemann, 2002.
[26] International Organization for Standardization, ISO 9001: Quality Management Systems—Requirements. Geneva, Switzerland: ISO, 2015.
[27] Japan P&I Club, Loss Prevention Bulletin: Hatch Cover Leakage and Cargo Damage. Tokyo, Japan: Japan P&I Club, 2021.