

From Rust to Reuse: Influence of Preload and Corrosion on the Mechanical Performance of Bolted Joints

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Abstract: Remanufacturing requires reliable assessment methods to evaluate the reuse potential of especially mechanically loaded components. Bolted joints are widely used in mechanical systems and play a critical role in assembly, disassembly, and remanufacturing processes. This study investigates the influence of preload, corrosion exposure on joint performance. Using M10 bolts, loosening torque and angle are measured after controlled tightening, salt spray corrosion, and reassembly with either reused or new bolts. Results show higher preload increases post-remanufacturing loosening torque and variability, while corrosion affects friction and torque distributions. Bolt replacement consistently improves torque retention. These experimental insights support data-driven remanufacturing decisions.

Keywords:

bolted joints, corrosion, loosening torque, remanufacturing, mechanical variability

1 Introduction

Under increasing pressure from resource scarcity, stringent environmental regulations, and the demand for economic efficiency, many industries are transitioning toward circular economy strategies [1]. The circular economy represents a fundamental shift from a linear “take–make–dispose” model to a closed-loop system, aiming to extend product lifetimes, retain material value, and reduce environmental impact. Within this framework, remanufacturing has emerged as a key enabler of sustainability and resource efficiency. [2]

Remanufacturing involves the systematic disassembly, inspection, cleaning, repair, and reassembly of end-of-life products in order to restore them to like-new or even enhanced functional performance. This approach is widely applied in sectors such as automotive engineering, heavy machinery, and industrial equipment, where components are often reused with warranties comparable to those of new products [3]. Despite its economic and ecological benefits, remanufacturing poses significant technical challenges, particularly with respect to ensuring the reliability and structural integrity of reused components [2], [4]. Among these, bolted joints play a critical role, as they must reliably withstand repeated assembly and disassembly cycles throughout a product’s lifecycle [5].

Bolted joints are especially susceptible to corrosion-induced degradation during service life. Corrosion alters surface conditions, friction coefficients, and material properties, thereby directly affecting the mechanical behavior of threaded connections. These changes have a direct impact on the torque–preload relationship, which is a key parameter for the functional integrity of bolted joints. One key manifestation of this degradation is the change in loosening behavior, commonly quantified by the breakaway (loosening) torque in comparison to the initial tightening torque. The ratio between breakaway torque and initial tightening torque is therefore a sensitive indicator of corrosion-related effects such as increased friction, thread adhesion, and surface damage caused by rust formation. Variations in this

torque ratio can indicate increased friction due to corrosion products, thread damage, or adhesion effects, all of which introduce uncertainty in joint preload and structural safety. In remanufacturing contexts, this uncertainty complicates decisions regarding component reuse, replacement, or requalification. [6]

Despite the practical relevance of this issue, there is a lack of systematic analysis linking corrosion progression in bolted joints to measurable changes in loosening torque behavior. Existing approaches often focus on visual inspection or qualitative corrosion assessment, which are insufficient for reliable mechanical evaluation. In particular, a quantitative comparison between initial tightening torque and measured breakaway torque under defined corrosion conditions is rarely addressed systematically. Consequently, a quantitative comparison of initial tightening torque and loosening torque under defined corrosion conditions is needed to better understand the mechanical implications of corrosion and to support robust decision-making in remanufacturing processes. [7]

The knowledge gained from this study can be directly fed back into product development. By understanding the conditions under which bolts can be safely reused, engineers can optimize joint designs for remanufacturing, improve maintenance protocols, and select materials and coatings that enhance long-term durability. This creates a data-driven basis for design decisions that support both sustainability and circular economy objectives. [8]

2 Methodology

This study employs a structured Design of Experiments (DOE) approach to systematically analyze the influence of corrosion on the loosening behavior of bolted joints. The experimental design is based on a full factorial $3 \times 3 \times 2$ layout with three primary controlled variables: (i) preload force (12 kN, 20 kN, 28 kN), (ii) corrosion exposure time (2 h, 4 h, 8 h), and (iii) configuration (new bolt, all old). Preload force (i) was varied at three levels (12 kN, 20 kN, 28 kN), representing under-tightened, nominal, and over-tightened assembly conditions [9]. Corrosion exposure time (ii) was likewise varied at three levels (2 h, 4 h, 8 h). These variables were selected because preload force directly governs the initial clamping condition and frictional state of the joint, corrosion exposure time represents the progression of surface degradation during service life, and the reassembly configuration reflects typical remanufacturing decisions regarding component reuse or replacement.

In addition to preload force (i) and corrosion time (ii), a third controlled variable was introduced during reassembly, namely the configuration (iii). Two remanufacturing scenarios are distinguished:

- **Replacement with new bolts:** This is the most common scenario, as bolts are widely available and inexpensive to replace. In contrast, the component into which the bolt is fastened often has a higher value, requires more CO₂-eq. and skilled labor to manufacture, and is less easily transported as a spare part. Therefore, preserving and reusing this component is of high interest.
- **Reuse of corroded bolts:** This scenario becomes particularly relevant when spare parts are unavailable or when the bolts are of a specific type that cannot be easily replaced

The experimental procedure follows a sequential workflow consisting of initial tightening, corrosion exposure, disassembly with loosening torque measurement, reassembly under defined remanufacturing conditions, and final loosening torque measurement. The loosening torque (LT) measured after the reassembly phase is defined as the target variable of this study, as it serves as an indirect indicator of the residual load-bearing capability of the bolted joint. Changes in loosening torque reflect alterations in frictional conditions, thread engagement, and preload retention, all of which are closely related to the joint's ability to maintain clamping force and mechanical integrity after remanufacturing. [9-11] By

comparing LT values across different preload forces, corrosion durations, and remanufacturing scenarios, the reuse potential of bolted joints can be quantitatively assessed.

The experimental framework describes a sequential procedure starting with initial assembly and controlled corrosion exposure, followed by disassembly and reassembly under defined remanufacturing scenarios, and concluding with final measurements. Throughout the process, experimental data are systematically collected and transformed into process and product data, providing the foundation for modeling and functional model development [8].

3 Experimental Setup

Standard M10 × 1.5 mm bolts in accordance with ISO 898-1, property class 8.8, were used as test specimens due to their widespread industrial application. Each bolted joint consisted of one bolt, one DIN 934 M10 nut, two DIN 436 square washers (11 × 30 × 3 mm), and one DIN 125 round washer (10.5 × 20 × 2 mm). An overview of the assembled joint prior to corrosion exposure is shown in Figure 1.



Figure 1: Experimental bolt assembly before corrosion: M10×1.5 mm ISO 898-1 Class 8.8 bolt, two DIN 436 square washers (11×30×3 mm), one DIN 125 round washer (10.5×20×2 mm), and a DIN 934 M10 nut

The overall experimental workflow for assembly, corrosion exposure, and remanufacturing assessment of bolted joints is illustrated in Figure 2. Prior to assembly, all bolts, nuts, and washers were cleaned for two minutes in an ultrasonic bath to remove surface contaminants that could influence friction and corrosion behavior. The components were then assembled and tightened using a Kistler INSPECTOR 5413-5103 electronic torque wrench. Tightening was performed to achieve the predefined preload forces of 12 kN, 20 kN, or 28 kN. Torque–angle data were recorded during tightening to ensure consistent assembly conditions. After initial tightening, the specimens were stored for 24h for settling. Later they were subjected to accelerated corrosion in a salt spray chamber for 2 h, 4 h, or 8 h. Corrosion was induced using a 15% hydrochloric acid solution. Custom-designed 3D-printed holders were employed to ensure uniform orientation and full exposure of the bolted joints to the corrosive mist. Following corrosion exposure, the specimens were dried and disassembled. The loosening torque was measured using the same Kistler torque wrench. During each disassembly process, the electronic torque wrench continuously recorded the torque–angle curve $M(\varphi)$. From this curve, the peak torque value corresponding to the breakaway event was identified and extracted. This peak value was then assigned to the respective bolt ID to ensure traceability throughout the dataset. The joints were then reassembled according to one of the two defined remanufacturing scenarios. In both cases, the joints were retightened to the same preload torque used during the initial assembly (12 kN, 20 kN, or 28 kN).

After reassembly, all specimens were stored for a minimum of 24 hours in a controlled environment at 20 °C and 55% relative humidity to allow for settling effects. Subsequently, the joints were disassembled again, and the final loosening torque and angle was recorded.

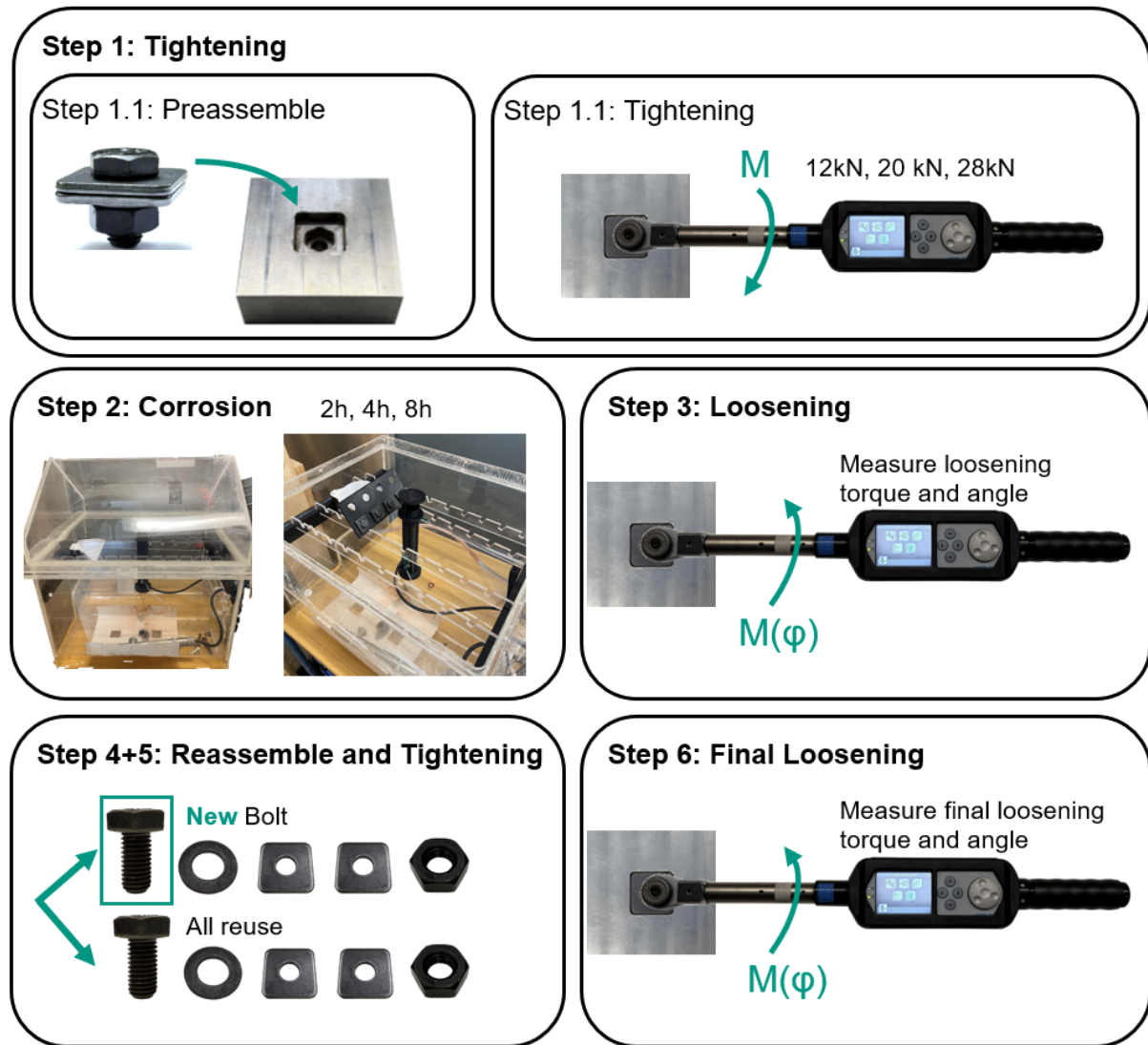


Figure 2: Experimental workflow for assembly, corrosion and remanufacturing assessment of bolted joints

Table 1: Experimental Design: Overview of experimental steps, controlled variables, recorded measurements, and sample sizes for corrosion and remanufacturing assessment of bolted joints.

Step	Controlled variable	Recorded value	Sample Size
1. Tightening	Preload force (12 kN, 20 kN, 28 kN)	Tightening angle (peak) Tightening torque (peak)	51 x 3 =153
2. Corrosion	Duration (2h, 4h, 8h)		(17x3) x3=153
3. Loosening		Loosening angle (peak) Loosening torque (peak)	153
4. Reassemble	New bolt All old		(10 [new bolt] + 7 [all old]) x3x3=153
5. Tightening		Tightening angle (peak) Tightening torque (peak)	153
6. Final Loosening		Loosening angle (peak) Loosening torque (peak)	153

The experimental workflow was structured into sequential steps, each associated with specific controlled variables and recorded measurements. Table 1 provides a detailed overview of these steps, indicating the variables that were systematically varied, the corresponding measurements collected at each stage, and the total number of samples for each configuration. This structured approach ensures that the influence of preload force, corrosion exposure, and reassembly condition on loosening torque and other mechanical responses can be quantitatively assessed across the full set of specimens.

4 Results

This study investigated the influence of preload force, corrosion exposure time, and remanufacturing method on the average percentage increase in loosening torque after reassembly. Data were grouped into 18 experimental conditions (3 preload levels x 3 corrosion durations x 2 reassembly configurations), allowing clear trends to be identified.

4.1 Correlation Between Loosening Torque, Tightening Torque and Angle

To analyze the relationship between applied tightening torque and loosening torque, Figure 3 presents a comparison of the peak tightening torque applied in Step 1 to achieve the three target preload levels with the corresponding initial loosening torque measured in Step 3. This visualization allows assessment of how different preload forces influence the initial mechanical behavior of the bolted joints and highlights the variability introduced by corrosion exposure during Step 2. The statistical analysis confirms the robustness of this trend, as all preload groups exhibited statistically significant differences (12 kN: $p = 0.0068$; 20 kN: $p = 0.0056$; 28 kN: $p = 0.00005$).

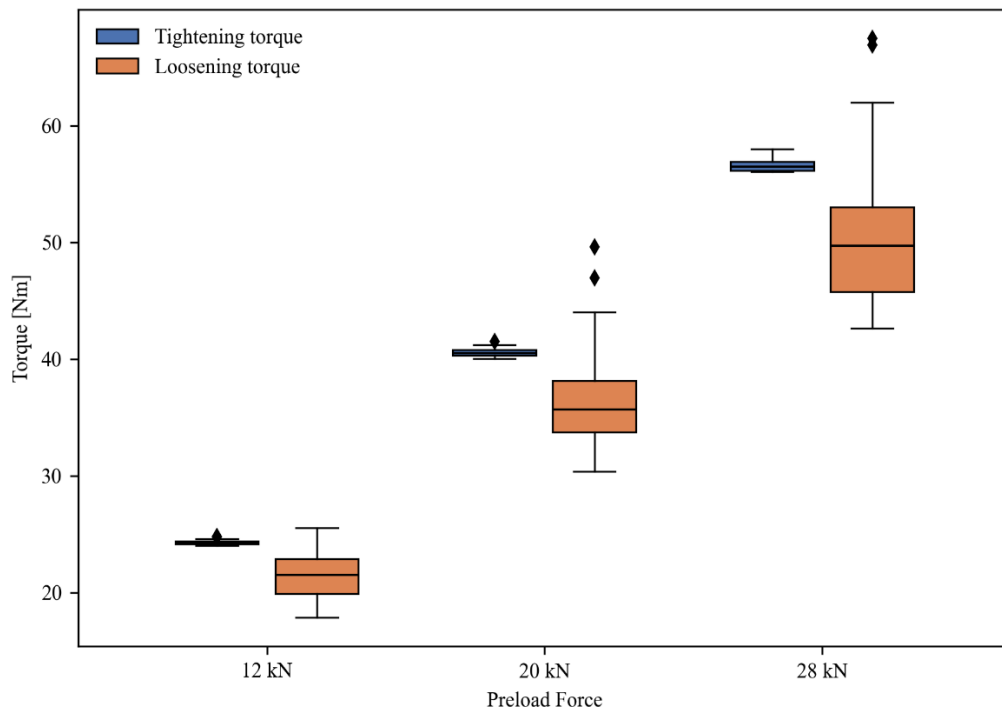


Figure 3: Boxplot of Tightening Torque (peak) of Step 1 and Initial Loosening Torque of Step 3 under three preload forces

Figure 4 presents a boxplot comparison of the peak tightening angle applied in Step 1 to achieve the three target preload levels with the corresponding initial loosening angle measured in Step 3. As expected, the median tightening angle increases with increasing preload, reflecting the additional rotation required to overcome higher thread friction and the friction between the bolt head and the washers. The distribution of tightening angles also becomes wider as the preload force increases,

indicating greater variability in the required rotation to reach higher clamping forces. This broader spread reflects the combined effects of friction variability and differences in thread engagement at elevated preload levels.

In contrast, the loosening angle is consistently lower than the corresponding tightening angle and shows a more compact distribution across all preload levels. The smaller variability reflects minor plastic thread deformations and stabilized friction after corrosion. Overall, while higher preload requires greater tightening rotations with a wider distribution, the initial loosening behavior remains relatively stable and less variable due to mechanical and frictional adjustments during corrosion and assembly.

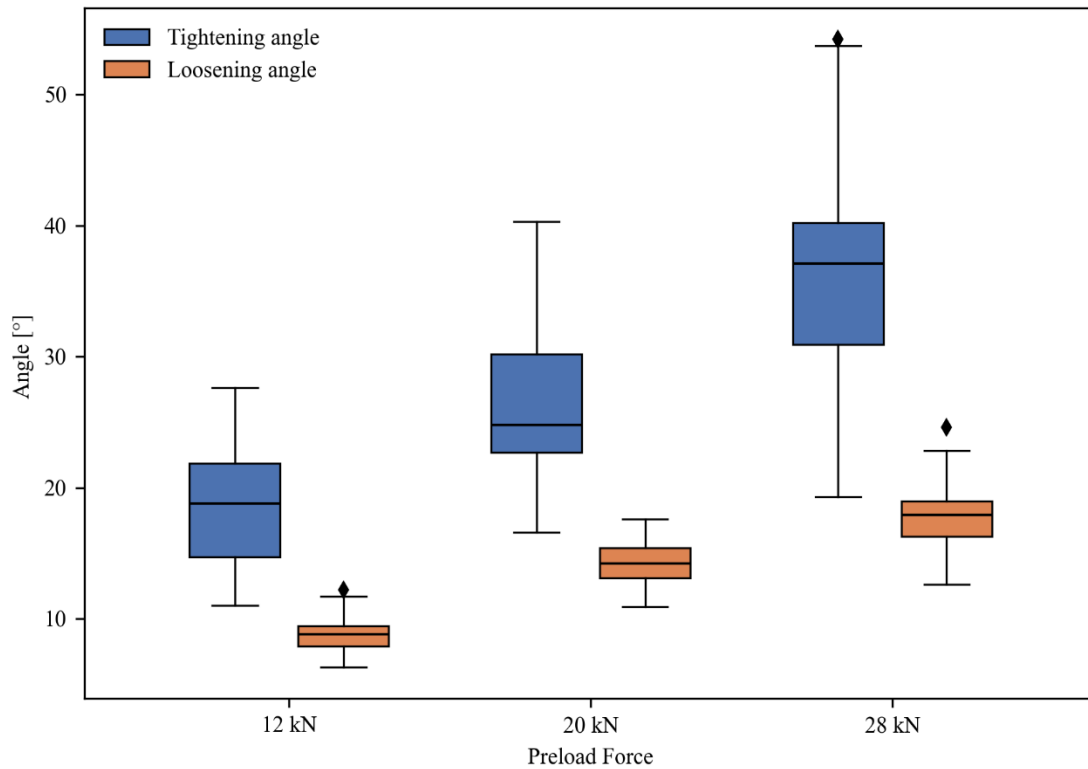


Figure 4: Boxplot of Tightening Angle (peak) of Step 1 and Initial Loosening Angle of Step 3 under three preload forces

Figure 5 shows the initial loosening torque measured in Step 3 following Step 1 tightening and Step 2 corrosion exposure for three different durations. Across all corrosion conditions, the main distribution of the initial loosening torque is wider than that of the applied tightening torque. The widest distribution was observed for the 4 h corrosion condition, indicating increased variability in joint behavior at this intermediate stage. This trend can be attributed to the evolving effects of corrosion at the bolted interface. Corrosion alters the surface condition of the threads and produces adhesion of corrosion products, which changes the local friction characteristics. After 2 h of exposure, corrosion is in its early stage, and its effect on all samples is relatively uniform, resulting in a narrower distribution. At 4 h, however, corrosion enters a transitional stage: the corrosion products are unevenly distributed across the bolt and nut surfaces, leading to greater variability in friction and, consequently, a wider spread in loosening torque values. After 8 h, the corrosion layer becomes more homogeneous and friction stabilizes, reducing the variability and narrowing the distribution of loosening torque compared to the 4 h condition.

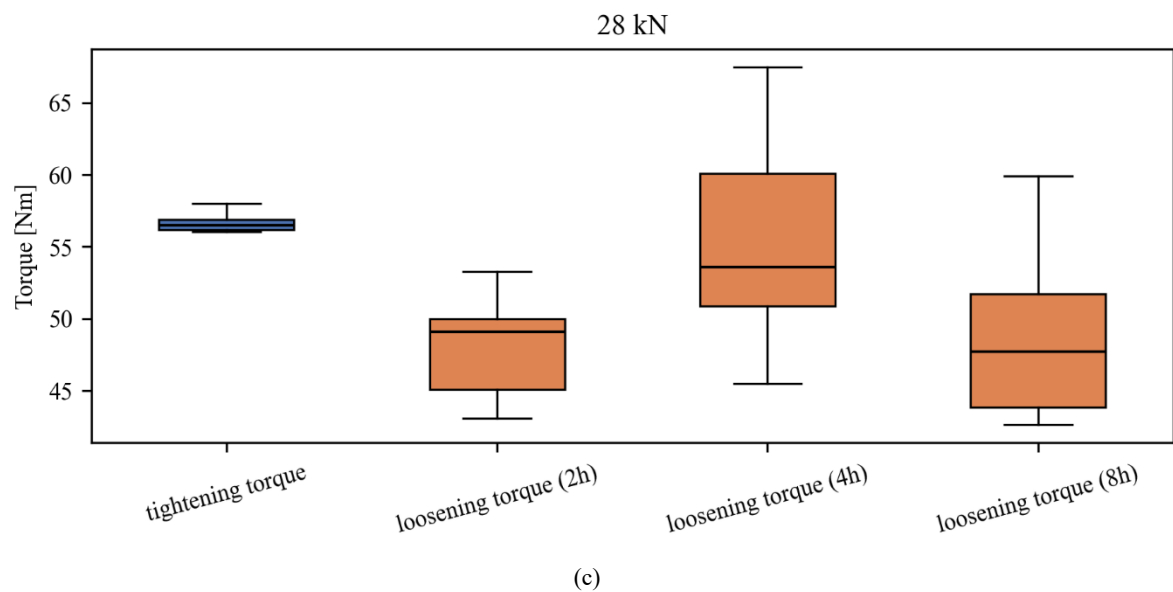
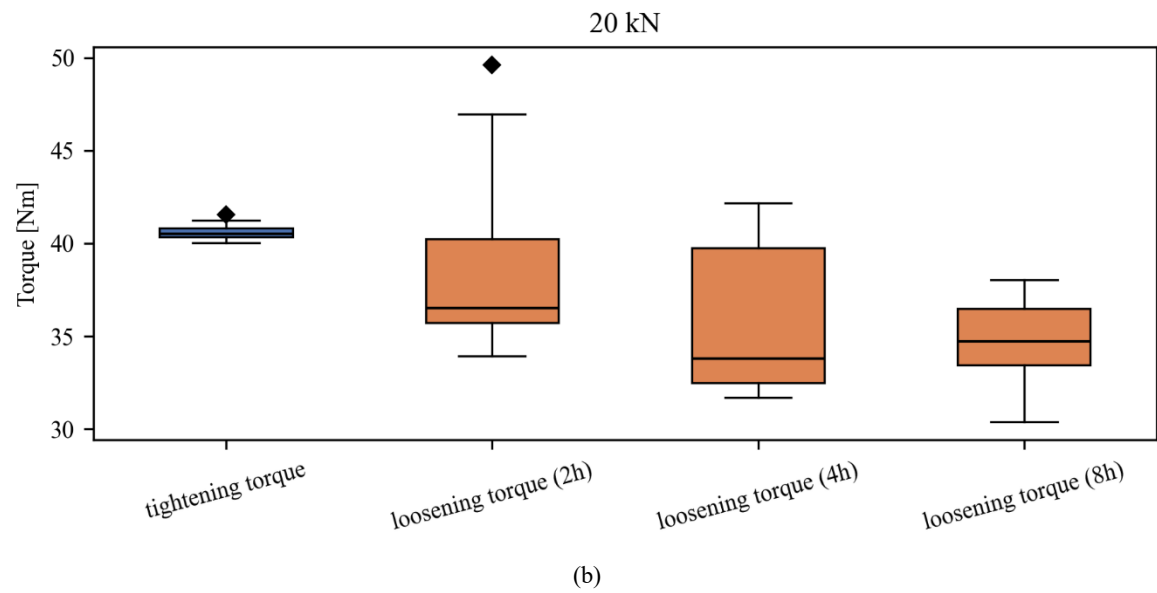
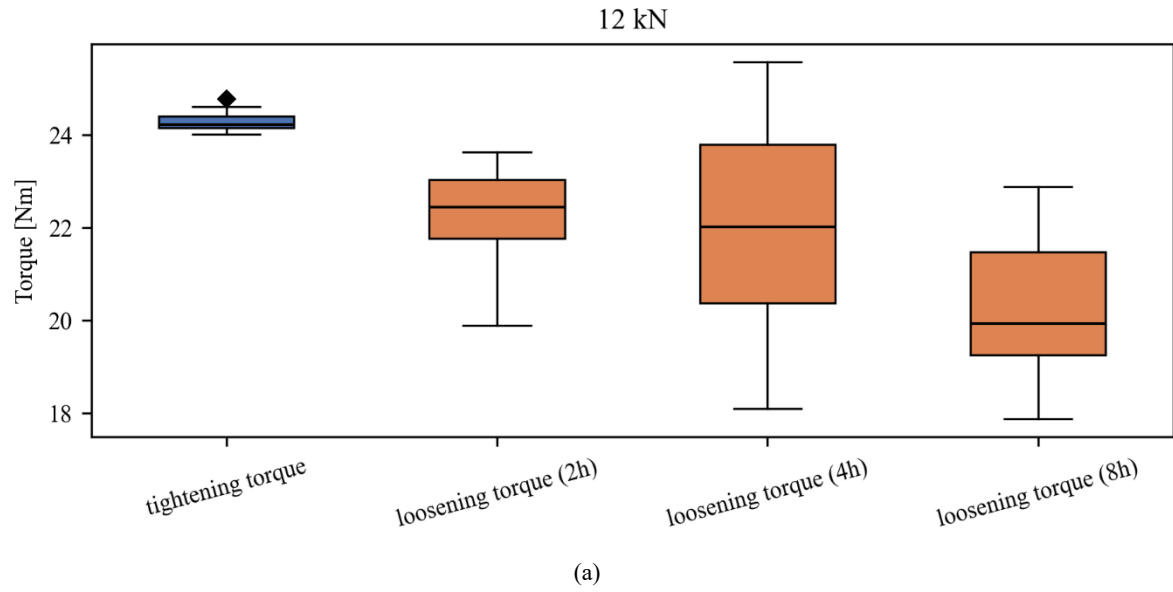


Figure 5: Boxplot of Tightening Torque (peak) of Step 1 and Initial Loosening Torque of Step 3 under Three Corrosion Durations and the Preload Forces (a) 12kN (b) 20 kN (c) 28 kN

4.2 Correlation between Loosening Torque and Final Loosening Torque

Of the 153 experimental samples, 145 exhibited an increase in final loosening torque (FLT) after reassembly compared to the loosening torque measured in Step 3. Only eight samples showed a decrease, with five occurring at a preload of 12 kN, two at 20 kN, and one at 28 kN. For each of the 145 samples showing an increase, the percentage increase in final loosening torque relative to the initial value was calculated. The average percentage increase for each experimental group is summarized in Table 2.

As preload force increased from 12 kN to 20 kN and 28 kN, the overall average percentage increase in final loosening torque rose correspondingly from 11.91 %, to 20.80 %, and 22.05 %, respectively. This trend suggests that higher preload forces promote greater torque retention after remanufacturing, likely due to improved initial clamping conditions and reduced micro-slipping at the interface under corrosion-induced stress.

Within each preload level, the effect of corrosion exposure time was also observed. Under 12 kN, the average percentage increase grew steadily with corrosion duration, from 6.26 % (2 h) to 13.07 % (4 h) and 16.38 % (8 h), indicating a positive correlation between corrosion exposure and torque increase. This is likely attributable to interface changes caused by corrosion, which increase friction during disassembly. In contrast, at higher preload forces (20 kN and 28 kN), the influence of corrosion time was less pronounced or even slightly diminishing. For instance, at 28 kN, the average increases were 25.44 %, 20.69 %, and 20.01 % for 2 h, 4 h, and 8 h, respectively.

Table 2: Average percentage increase in final loosening torque compared to initial loosening torque of step 3 - Loosening in each experimental group

Step 1	Step 2	Step 3		Step 4	Step 6 – Final Loosening Torque (FLT)				
Preload force	Corrosion level	Loosening Torque (LT)		Retightening configurations	average percentage increase $X = \frac{FLT-LT}{LT}$				
		$\overline{LT}$ [Nm]	Var(LT)		$\overline{FLT}$ [Nm]	Var(FLT)	X [%]		
12 kN	2h	22.21	1.82	New bolt	23.90	1.95	7.58	6.26	11.91
				All old	23.11	1.45	4.37		
	4h	21.85	5.23	New bolt	24.32	4.60	11.52	13.07	
				All old	24.91	4.82	15.30		
	8h	20.36	2.45	New bolt	23.99	2.94	16.72	16.38	
				All old	23.17	4.36	15.90		
20 kN	2h	38.76	19.77	New bolt	47.24	12.11	22.45	21.31	20.80
				All old	45.44	48.15	19.69		
	4h	35.62	15.45	New bolt	44.12	21.11	24.11	20.25	
				All old	40.45	3.19	14.73		
	8h	34.62	5.95	New bolt	43.30	11.80	26.13	20.83	
				All old	39.35	6.29	13.26		
28 kN	2h	47.99	10.09	New bolt	60.78	25.43	27.04	25.44	22.05
				All old	59.24	33.13	23.16		
	4h	55.45	42.84	New bolt	69.67	103.43	25.59	20.69	
				All old	62.05	24.27	13.69		
	8h	48.22	21.97	New bolt	57.41	18.13	19.58	20.01	
				All old	57.72	3.32	20.63		

Across all conditions, replacement of the bolt during remanufacturing resulted in a higher average percentage increase than reusing all original components. For example, at 20 kN and 4 h, bolt replacement yielded an average increase of 24.11 %, compared to 14.73 % when all original components were reused. This pattern was consistently observed across most experimental groups, confirming that bolt replacement enhances post-remanufacturing joint performance, likely due to improved thread engagement and reduced surface degradation. Overall, a greater increase in loosening torque indicates improved residual clamping strength and frictional resistance, both of which contribute positively to the durability and reliability of remanufactured bolted joints

5 Discussion

The results of this study provide clear insights into how preload force, corrosion exposure, and remanufacturing method influence the mechanical behavior of bolted joints. The observed trends in loosening torque and angle distributions reveal the combined effects of thread friction, surface degradation, and interface changes due to corrosion.

Higher preload forces were found to increase both the average loosening torque after reassembly and the variability of tightening torque and angle. Mechanically, this can be attributed to improved initial clamping conditions that reduce micro-slipping under corrosion-induced stress. However, the wider spread in tightening torque and angle at higher preload forces indicates that achieving target preload requires overcoming greater frictional resistance, including friction between the bolt head and washers, as well as along the thread surfaces. This variability highlights the importance of precise torque application in both original assembly and remanufacturing contexts. Corrosion significantly affects loosening behavior by altering surface conditions at the bolt–nut interface. These findings confirm that the stage of corrosion development critically influences both the mean and the scatter of loosening torque, emphasizing the need to consider corrosion history when evaluating the reuse potential of bolts.

The comparison between remanufacturing scenarios demonstrates that bolt replacement generally provides higher residual torque retention than reusing corroded bolts. This effect is likely due to the restoration of optimal thread engagement and the elimination of localized surface degradation, which mitigates frictional inconsistencies. In contrast, reused bolts carry accumulated wear and corrosion, which can limit torque recovery and increase variability. Therefore, while reusing corroded bolts may be feasible under controlled conditions, bolt replacement offers a more reliable approach for maintaining joint performance.

It is important to note the limitations of the current study. Only a finite number of samples were tested, which limits the statistical generalizability of the results. Furthermore, no direct measurements of mechanical strength or load-bearing capacity were performed; future studies could include tensile or fatigue tests to evaluate the actual structural performance of the joints. In addition, the experimental setup did not subject the bolts to vibrations, which are common in real-world applications. Vibrations could promote bolt loosening and allow deeper penetration of corrosion products, potentially altering torque behavior and variability. These factors should be addressed in follow-up experiments to better simulate in-service conditions.

Overall, these findings provide valuable insights into the influence of preload, corrosion, and remanufacturing method on bolted joint behavior. They also highlight the need for further testing under more realistic operational conditions to fully assess joint reliability and to develop predictive models for remanufacturing and maintenance strategies.

6 Summary

The experimental results demonstrate that both preload force and corrosion exposure significantly affect the loosening behavior of bolted joints. Higher preload forces generally lead to increased post-remanufacturing loosening torque and wider distributions of tightening angle and torque, reflecting greater frictional resistance and variability in thread engagement. Corrosion alters the surface condition of the threads, producing adhesion of corrosion products and modifying friction, which in turn influences both torque and angle measurements. The variability of initial loosening torque is greatest at intermediate corrosion durations. Bolt replacement during remanufacturing consistently results in higher average percentage increases in loosening torque compared to reusing all original components, highlighting the benefit of improved thread engagement and reduced surface degradation. Overall, these findings indicate that careful consideration of preload, corrosion exposure, and remanufacturing method is essential for predicting residual clamping strength and ensuring the reliability of remanufactured bolted joints.

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References

- [1] P. Majumder und H. Groenevelt, „Competition in Remanufacturing“, *Production and Operations Management*, Bd. 10, Nr. 2, S. 125–141, 2001, doi: 10.1111/j.1937-5956.2001.tb00074.x.
- [2] J. P. Jensen, S. M. Prendeville, N. M. P. Bocken, und D. Peck, „Creating sustainable value through remanufacturing: Three industry cases“, *Journal of Cleaner Production*, Bd. 218, S. 304–314, Mai 2019, doi: 10.1016/j.jclepro.2019.01.301.
- [3] M. Matsumoto, S. Yang, K. Martinsen, und Y. Kainuma, „Trends and research challenges in remanufacturing“, *Int. J. of Precis. Eng. and Manuf.-Green Tech.*, Bd. 3, Nr. 1, S. 129–142, Jan. 2016, doi: 10.1007/s40684-016-0016-4.
- [4] S. Sitcharangsie, W. Ijomah, und T. C. Wong, „Decision makings in key remanufacturing activities to optimise remanufacturing outcomes: A review“, *Journal of Cleaner Production*, Bd. 232, Mai 2019, doi: 10.1016/j.jclepro.2019.05.204.
- [5] J. Kurilova-Palisaitiene, E. Sundin, und B. Poksinska, „Remanufacturing challenges and possible lean improvements“, *Journal of Cleaner Production*, Bd. 172, S. 3225–3236, Jan. 2018, doi: 10.1016/j.jclepro.2017.11.023.
- [6] S. Mangold, E. Gerlitz, S. Zimprich, M. Friedmann, S. Matthiesen, und J. Fleischer, „Systematic quantitative investigation of the unscrewing process with regard to breakaway torque“, *Jnl Remanufactur*, Bd. 13, Nr. 1, S. 53–66, März 2023, doi: 10.1007/s13243-022-00120-x.
- [7] C. Jiang, W. Xiong, C. S. Cai, Y. Zhu, und J. Wang, „Preload loss of high-strength bolts in friction connections considering corrosion damage and fatigue loading“, *Engineering Failure Analysis*, Bd. 137, S. 106416, Juli 2022, doi: 10.1016/j.engfailanal.2022.106416.
- [8] N. Afifi, J.-P. Kaiser, A. Wettstein, G. Lanza, und S. Matthiesen, *Data-Driven Functional Modeling of Corroded Bolted Joints: A Framework for Remanufacturing*. 2025. doi: 10.1115/IMECE2024-145271.
- [9] *VDI 2230 Blatt 1 - Systematische Berechnung hochbeanspruchter Schraubenverbindungen - Zylindrische Einschraubenverbindungen*. 2015. Zugriffen: 20. Januar 2026. [Online]. Verfügbar unter: <https://www.vdi.de/mitgliedschaft/vdi-richtlinien/details/vdi-2230-blatt-1-systematische-berechnung-hochbeanspruchter-schraubenverbindungen-zylindrische-einschraubenverbindungen>
- [10] J. Shah, H. Wang, A. Mukherjee, J. Shah, H. Wang, und A. Mukherjee, „Investigating the Correlation Between Corrosion-Induced Bolt Head Damage and Preload Loss Using Ultrasonic Testing“, *Sensors*, Bd. 25, Nr. 14, Juli 2025, doi: 10.3390/s25144491.
- [11] R. G. Budynas, K. J. Nisbett, J. K. Nisbett, und J. E. Shigley, *Shigley's mechanical engineering design*, 10. ed. in SI units. in McGraw-Hill series in mechanical engineering. New York, NY: McGraw-Hill Education, 2015.