Study on Analytical Verification Method for Dynamic Load Profile-based Joint Design

J.H. Kim[1], S.D. Kim[2], K.T. Lee[2]

[1]Hyundai Motor Company
[2]KoreaSimulationTechnologies (KOSTECH)

1 Introduction

Fastening is clamping and fixing objects using tensile force generated by applying torque to bolts or nuts. In this process, the applied torque doesn't entirely convert to bolt's axial force (clamping force); It is mostly lost due to friction, and only a portion is transmitted as axial force. Typically, around 90% of the torque is lost. These frictional losses are influenced by factors like the shape and material of the joint parts and surface finishing. As depicted in Fig.1, even small change in friction coefficient can have a significant impact on the resulting clamping force.

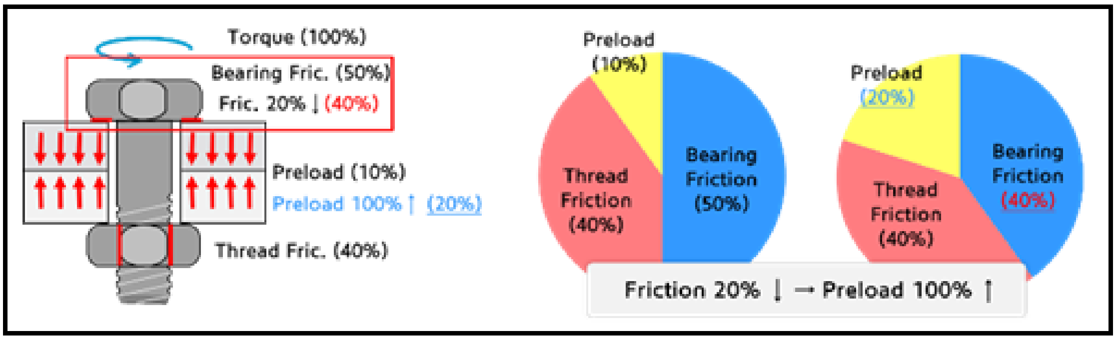

Fig.1: Preload (Clamping force) – Friction Relationship

In other words, when torque is applied to generate clamping force, the force transmitted as clamping force is influenced by friction and the geometry of the fastener. The relationship between torque, clamping force, friction coefficient can be expressed as follows:

$$\mathrm{T} = \mathrm{K} \times \mathrm{F} \times \mathrm{d}$$

$$\mathrm{K} = \frac{1}{2\mathrm{d}}[\frac{P}{\pi} + \mu_{th} d_2 \sec\left(\frac{\pi}{6}\right) + \mu_b D_w]$$

Excluding the fastener geometry factors (d, d_2, P, D_w), the relationship between torque and clamping force is determined by friction coefficient. These friction coefficients inherently have some deviation, so even when the bolted joint fastened with same torque, the resulting clamping force will have some dispersion.

Considering this dispersion in clamping force, designing a stable bolted joint involves calculating the minimum required clamping force (F_{bmin}) and the maximum allowable clamping force (F_{bmax}). The range of clamping force should be positioned between these two values to ensure stability. The minimum required clamping force is the minimal force needed to prevent bolt loosening and joint separation due to external loads. This is determined through methods like Finite Element Analysis (FEA) and experimental measurements, accounting for shear loads and preload loss caused by external forces. The maximum allowable clamping force is the maximum force that the bolted joint assembly can withstand without fail or sinking. This is determined through methods like FEA and experimental measurement, considering factors like fatigue, yielding, and fracture. The process of deriving those two value, calculating the clamping force range, and generating the fastening specification to ensure that the clamping force range is stably positioned between the two value is referred to as joint design analysis.

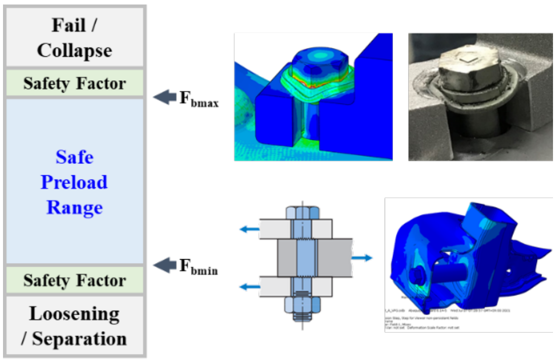

Fig.2: Joint Design Analysis

Thus, in this study, external loads were applied to Chassis joint using LS-DYNA to simulate the behavior of the joint. Subsequently, joint design analysis factors were calculated.

2 Joint Analysis based on Dynamic Load Profile

2.1 Analysis method

Dynamic load profiles measured through strain-gauge on the Chassis joint were applied to FEA Model using LS-Dyna, and the resulting behavior of the joint was observed. Through this study, shear force, preload loss, slip of joint interface, and fatigue were determined.
The load on the bolted joint affects their behavior in different ways by direction. Shear forces in the transverse direction impact bolt loosening, while axial forces influence fatigue failure. Therefore, by measuring shear and axial forces on the joint under dynamic loads, it's possible to verify the stability of bolt loosening and fatigue limits. Additionally, under applied loads, yielding deformation among joint parts can lead to decrease in clamping force. Slip between joint interfaces can cause quality problem such as bolt loosening, noise and dislocation. Hence measuring slip between joint parts were taken under dynamic loads.

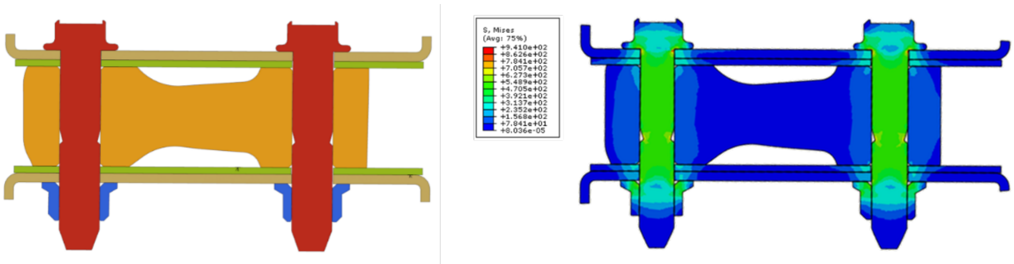

Fig.3: Chassis joint FEA Model

2.1.1 Shear Force

When using LS-DYNA, shear forces on contact surfaces are not directly calculated. Therefore, a local coordinate system was established perpendicular to the bolt's axial and transverse directions to calculate shear and axial loads separately.

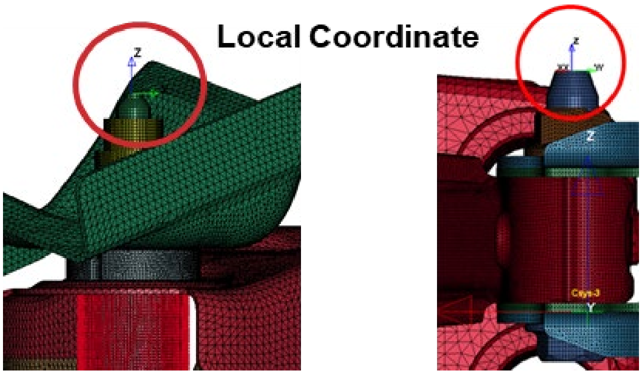

Fig.4: Local coordinate location for shear load measurement

2.1.2 Preload Loss

A cross-section normal to the bolt axis direction was created in the shank part of the bolt, and bolt preload is generated by creating initial stress section. The bolt preload loss by applied dynamic loads was calculated by LS-DYNA.

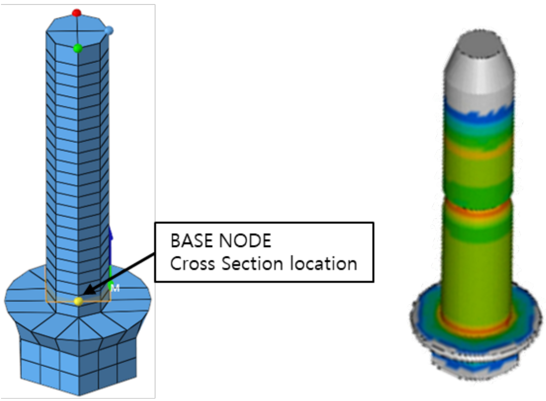

Fig.5: Cross-section location and bolt preload

2.1.3 Interface Slip Estimation

There are various methods for calculating slip occurrence between joint parts. In this study, slip occurrence and magnitude between two adjacent parts are calculated by computing the displacement between nodes of these parts. External loads, preload loss and shear force are compared at the point of slip occurrence between components.

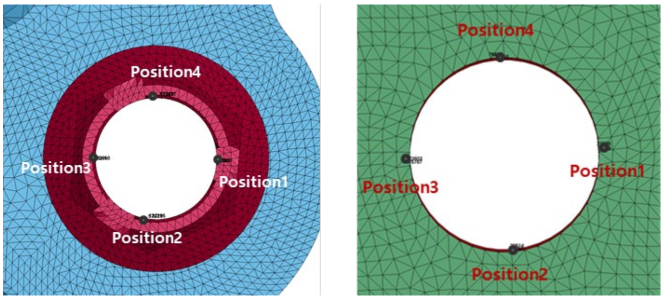

Fig.6: Node location for computing the displacement between parts

2.1.4 Fatigue

In the fatigue limit analysis of the bolt, S-N curve obtained through experiments is applied to LS-DYNA and conducted fatigue analysis with Goodman and Gerber mean stress corrections under a load duration of 10^18 seconds. To ensure a more conservative analysis, the analysis is conducted under tension-only conditions.

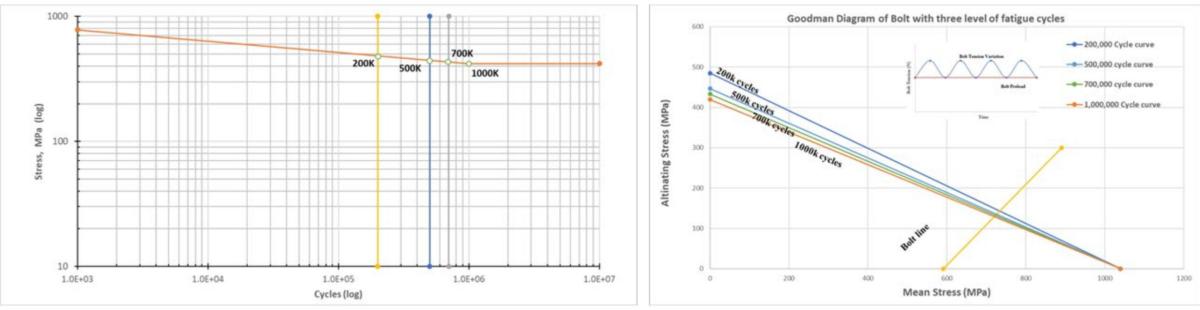

Fig.7: Applied S-N curve

3 Joint Analysis Result

The applied dynamic load on the bolted joint is as follows, and upon observing the entire profile, it can be confirmed that there is a momentary peak load occurring around 20 seconds. In particular, since the Y and Z directions loads align with the shear direction of the bolt, it is expected that these loads will have a significant impact on the slip between joint parts and preload loss.

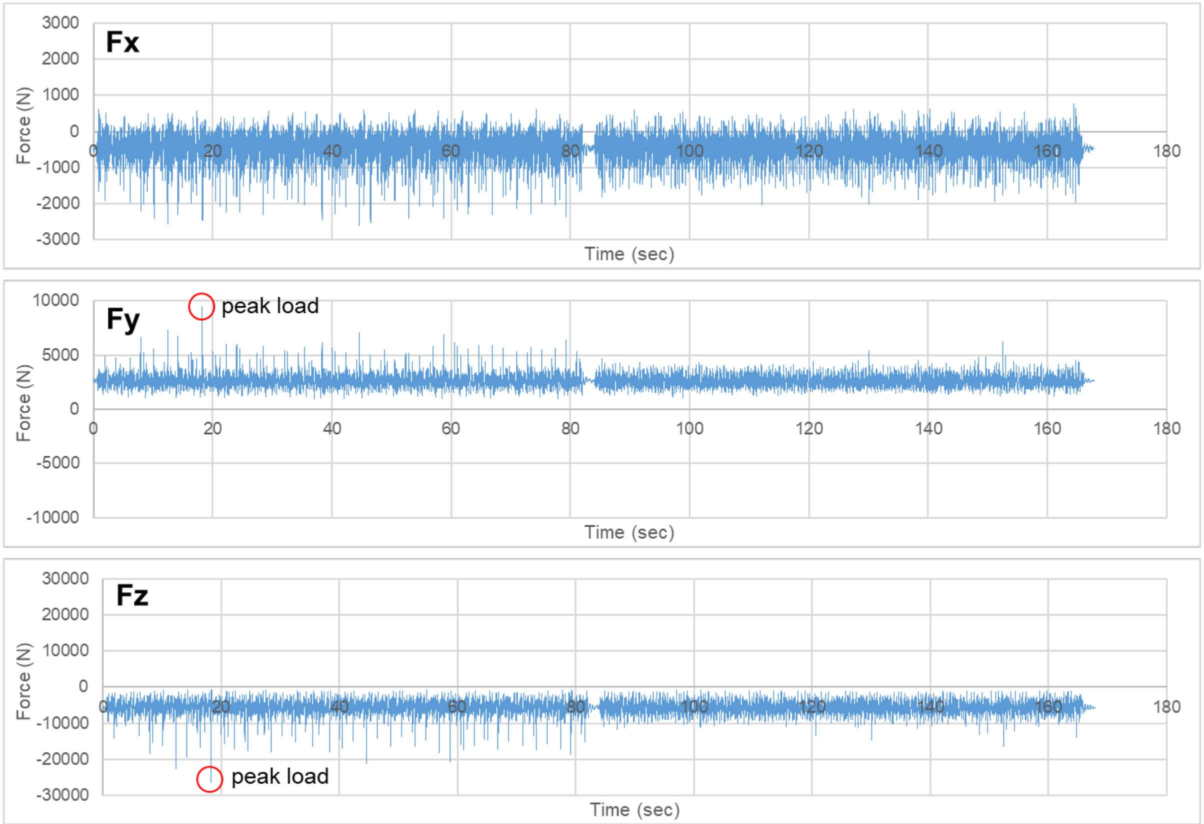

Fig.8: The applied dynamic load

The interfaces between the Chassis joint are composed of Bush – Bracket, Bolt – Bracket, and Nut – Bracket, respectively. The measured shear loads at each interface are as follow, and since the load is applied from the Bush and transmitted to Bracket and fastener, the highest shear load occurred at the interface between Bush and Bracket, while a small shear load was observed between fastener and Bracket. Furthermore, as previously confirmed, the maximum shear load values at each interface occurred around the 20 second mark during the peak load event, and it can be observed that the shear load profile shifted upwards.

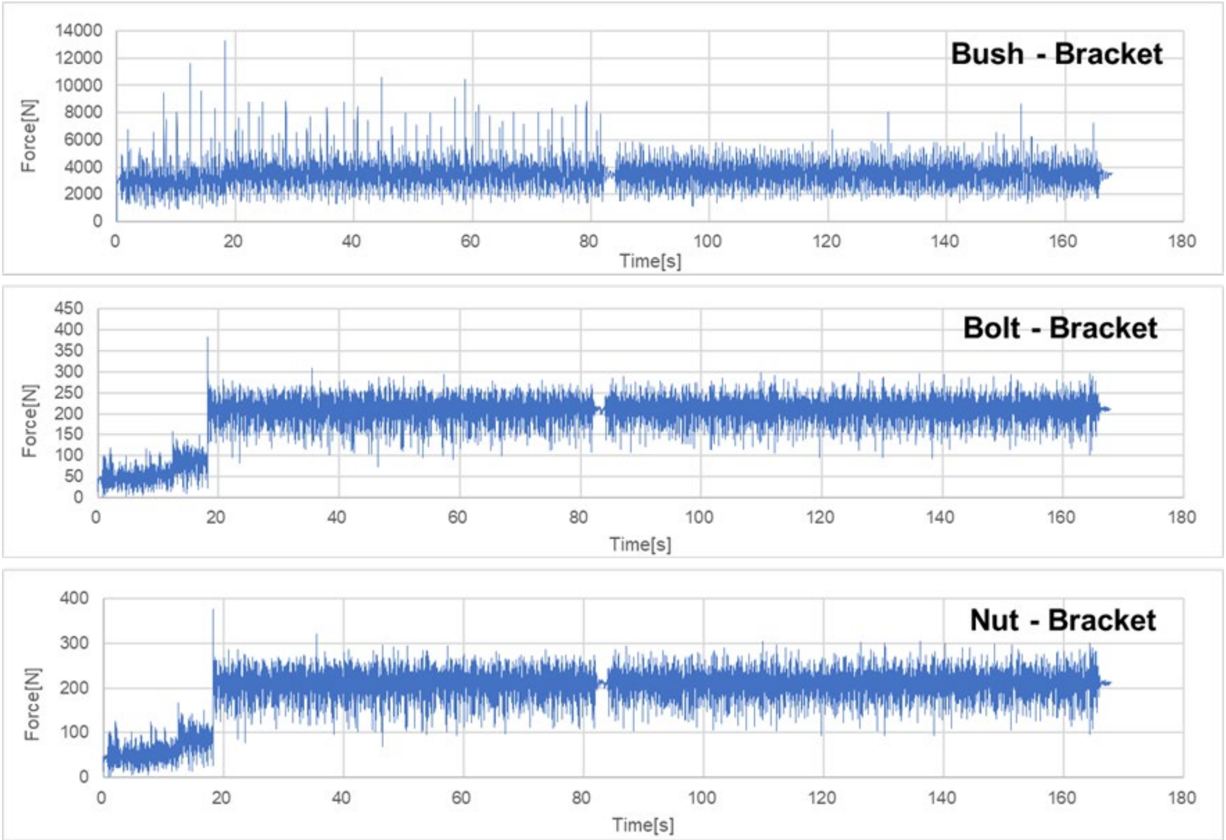

Fig.9: Shear load profile

It has been confirmed that local yield deformation of the joint due to external loading and the changes in clamping force caused by slippage exhibit a similar trend to the previously mentioned shear load values. As a result of external loading, there is a slight decrease in clamping force due to the embedding of joints and local deformation, but around the 20-second mark, a momentary slip occurs, leading to significant reduction of calmping force.

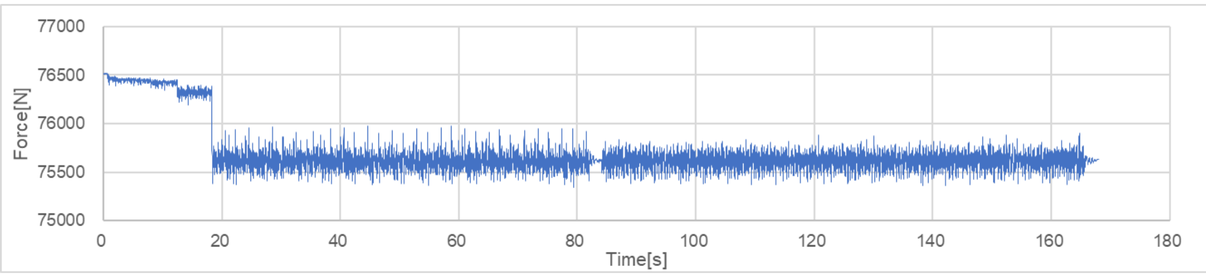

Fig.10: Clamping force change graph

The measurement results of slip at the joint interfaces can be seen in the following figure. As shown, slip occurred at around 20 seconds at all interfaces, while minor slips occurred at other times, but they were confirmed to be at levels where elastic recovery is possible. The difference between max load and second max load in the load profile is approximately 4300 N. However, slip only occurred at max load and not at second max load. This suggests that there is a critical load at which slip occurs, and if the applied load is less than this critical load, slip is not expected to occur. Therefore, it appears possible to determine a clamping force value with slip critical load higher than the max load through reverse engineering, which would result in no slip. This will be validated through further analysis and experiments in the future.

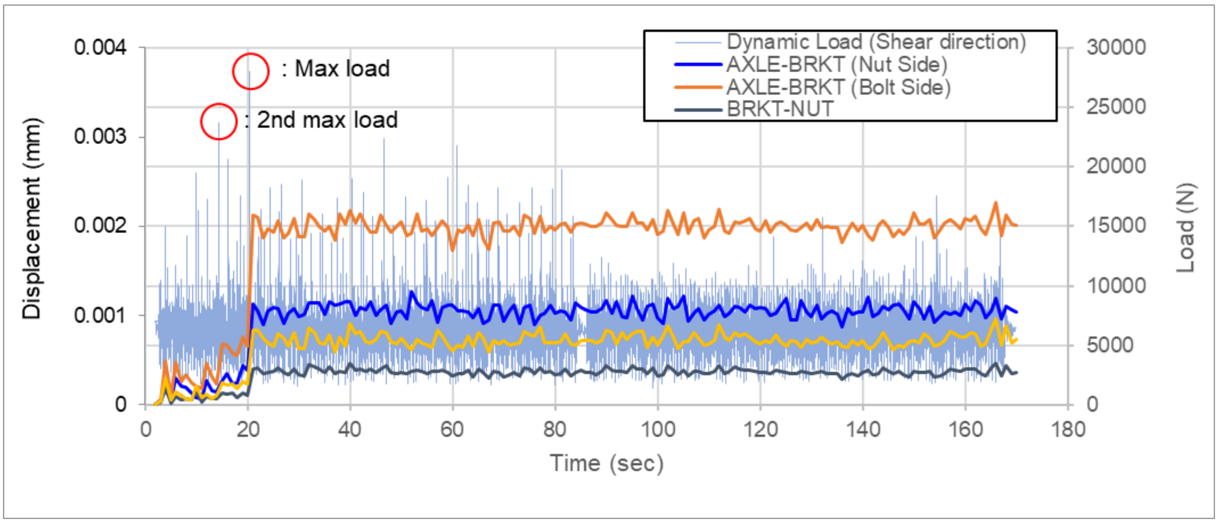

Fig.11: Slip measurement and load profile

Fatigue analysis was conducted using the GOODMAN and GERBER mean stress correction methods in LS-DYNA as previously introduced. The loading was applied under tension-only conditions for a duration of 10^18 seconds. The fatigue analysis results indicated that both GOODMAN and GERBER methods produced an infinite fatigue life in terms of damage ratio and expected fatigue life.

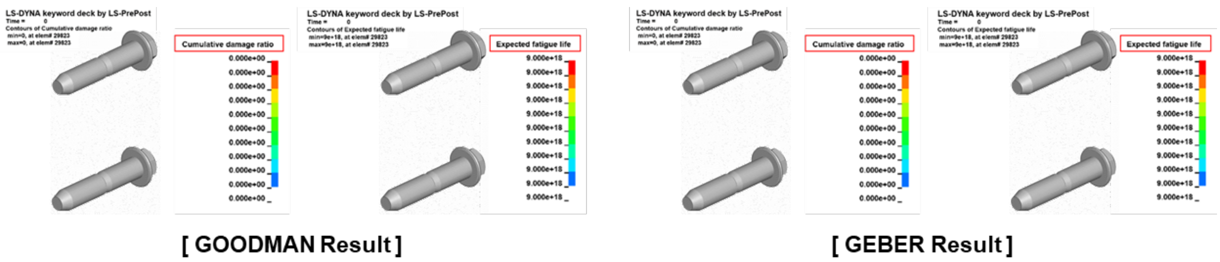

Fig.12: Fatigue Analysis Result

4 Summary

Through this study, the bolted joint was modeled using LS-DYNA, and when the measured dynamic loads from the durability test were applied to the model, it simulated the behavior of the joint. In the verification of joint design, factors such as shear load, preload loss, slip between joint interfaces, damage ratio, and fatigue life that significantly impact bolt loosening and durability performance were calculated. Under dynamic loading conditions, shear load and slip were found to be most significant at the interfaces between joint parts where external forces were directly applied, and it was confirmed that slip occurred between joint interfaces during momentary load peaks, leading to a reduction in clamping force and shear load peaks. These results suggest that by reverse engineering to determine clamping force that do not cause slip, robust bolted joint can be designed to prevent slip and preload loss during durability process, thus preventing issues such as bolt loosening or misalignment. In the case of fatigue analysis, it was verified that even under tension-only conditions, both fatigue life and damage ratio were infinite, ensuring the stability against fatigue failure due to durability testing.

5 Literature

[1] Brickford, J., Handbook of bolts and bolted joints, CRC press, 1998

[2] Sakai, T., Bolted joint engineering: Fundamentals and applications, Beuth Verlag, 2008
[3] Haviland, G. S., Designing with threaded fasteners, Loctite Corporation, 1983
[4] Tanaka, M., Hongo, K., Asaba, E., Finite element analysis of the threaded connections subjected to external loads, Bulletin of JSME, 25(200), 291-298, 1982
[5] ISO 898-1, Mechanical properties of fasteners made of carbon steel and alloy steel, 2013
[6] ISO 16047, Fastbers-Torque/clamp force testing, 2005
[7] J. H. Kim, Study on enhancing cambolt yield load by optimizing friguration, JKSPE, 2022
[8] S. K. Kang, S. H. Kim, Predictive model for bearing torque in bolt fastening, CIRP Annals, Volume 71, Issue 1, 489-492, 2022