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Effect of Bolt Preload and Friction on Slip and Yield in Steel Bridge Connections

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ABSTRACT

This study analyzes the effect of bolt preload and friction coefficient on slip capacity and yield in steel truss bridge connections using the finite element method (FEM) through Abaqus software. Preload variations ranging from $0.2f_y$ to $0.9f_y$ and friction coefficients between 0.3 and 0.5 were applied to find the relationship between these factors. The results indicate that increasing preload and friction coefficient enhances slip capacity. Specifically, at a preload of $0.2f_y$ and friction coefficient of 0.3, slip occurred at 1549.07 kN, whereas at a preload of $0.9f_y$ and friction coefficient of 0.5, the slip capacity reached 11354.1 kN. However, excessive preload ($>0.7f_y$) can lead to local failure due to stress concentration around the bolt hole. Validation using the AISC analytical method showed an average difference of only 1.6% with a maximum error of 5.28%, indicating a high level of accuracy in the FEM model. These findings provide recommendations for optimal connection design, suggesting a preload of $0.7f_y$ and a friction coefficient of 0.5 to enhance connection capacity while mitigating the risk of premature failure.

Keywords: bolt preload, friction coefficient, slip capacity, yield capacity, and steel truss bridge connection.

INTRODUCTION

A steel truss bridge is one of the most widely used structural types in transportation infrastructure due to its ability to withstand heavy loads and span long distances. Its design flexibility allows for adaptation to various geographical conditions, while ease of construction and maintenance makes it a preferred choice for numerous infrastructure projects, particularly in remote areas or archipelagic regions [1]. However, despite its advantages, one of the main challenges in the design and maintenance of steel truss bridges lies in the performance of their connections, particularly bolted joints, which play a crucial role in the overall structural stability and load-bearing capacity.

Bolt preload and the friction coefficient at the joint interface are two key factors that determine the strength and durability of connections. Insufficient preload can lead to joint slippage due to shear forces, while excessive preload may cause excessive stress concentration around the bolt hole, increasing the risk of material failure [2]. Additionally, the friction coefficient between the joint surfaces plays a crucial role in slip capacity. Research has shown that both static and dynamic friction coefficients influence the contact force and normal force between the connected elements [3]. In the context of steel bridge connections, the normal force generated by bolt preload affects stress distribution, particularly under vehicular loads, making friction coefficient optimization essential for maintaining joint stability.

Several previous studies have explored how bolt preload and friction coefficient contribute to the strength of bolted connections. There are four primary stages in the failure of bolted joints: the friction stage, the slip stage, the bearing stage, and the total failure stage [4]. Additionally, the friction coefficient significantly influences the initial strength of the connection, as a low friction coefficient can lead to a reduction in joint strength and potentially affect fatigue life [5]. Bolt pretension can enhance the shear strength of the connection and reduce the likelihood of slip [6]. Surface treatment also plays a crucial role in the slip factor, with traditional methods such as grit blasting yielding slip factors of only 0.14–0.24, whereas innovative methods like anti-slip coatings can increase the slip factor up to 0.58 [7].

The mechanisms of slip and yield failure are also critical concerns in the study of bolted connections. Finite element modeling (FEM) and experimental studies have been employed to evaluate the maximum load capacity of connections with varying steel web member thicknesses. Research findings indicate that increasing the web member thickness can enhance load capacity by up to 3.87 times the initial design load [8]. Beyond slip failure, yield failure due to plastic deformation is another major consideration in connection design. Bolt preload can increase the total capacity of high-strength steel connections by 15% to 29%, with frictional force contributing 18% to 32% of the total capacity [2]. However, this benefit diminishes due to plastic deformation in the bolts, leading to pretension loss under loading, where the frictional contribution drops to only 3% [2]. Slip capacity can increase by 35.71% when preload is raised from $0.53f_y$ to $0.72f_y$, while an increase in the slip factor from 0.31 to 0.55 can enhance slip capacity by up to 77.42% [4].

In addition to mechanical aspects, environmental factors can also influence the performance of bolted connections. Corrosion caused by environmental exposure, such as humid air, rain, and pollutants, can reduce surface roughness and friction effectiveness in joints, ultimately decreasing slip capacity [9]. High-humidity environments, extreme temperatures, and chemical exposure accelerate the degradation of joint surfaces, leading to a reduction in slip capacity and long-term durability [10]. Furthermore, preload loss due to material relaxation is another critical concern. Preload loss occurs in three main phases: short-term loss due to surface readjustment, mid-term loss due to material creep, and long-term loss caused by dynamic loading cycles and environmental effects [11].

Concerning friction effectiveness in bolted connections, contact displacement between the two joint elements occurs in two primary directions: normal and tangential. The normal direction generates pressure perpendicular to the surface, while the tangential direction produces friction that depends on both static and dynamic friction coefficients [12]. If the preload is high but the friction coefficient is low, the resulting friction force may still be insufficient to prevent slip. Conversely, a higher friction coefficient can enhance slip capacity without the need for excessive preload, thereby reducing the risk of excessive stress on the bolts [13].

The finite element method has proven to be effective in analyzing the capacity and failure mechanisms of gusset plate connections in truss bridges. The experimental-based Whitmore model was successfully validated with actual data, demonstrating high accuracy in predicting connection capacity. Analytical results revealed that failure could occur at lower loads than predicted by traditional methods, with a maximum recorded capacity of 91.84 kips and yielding occurring at 92% of the applied load. This study recommends further testing to understand the influence of member thickness and improve evaluation and rehabilitation methods for gusset plate connections [14].

Based on various previous studies, the relationship between preload and friction coefficient plays a crucial role in determining the slip and yield capacity of bolted connections. However, there remains a gap in understanding the simultaneous influence of preload and friction coefficient variations on the mechanical behavior of bolted connections in steel truss bridges.Therefore, this study employs a numerical approach using the Finite Element Method (FEM) through Abaqus software, validated against analytical methods developed in prior research. The primary objective is to provide recommendations for optimizing connection design while enhancing the reliability and durability of bolted connections in steel truss bridges. Additionally, the findings of this study are expected to serve as a reference for bridge maintenance, helping to mitigate the risk of failure due to improper bolt preload application and extending the service life of steel truss bridges in Indonesia.

RESEARCH METHODS

Selection of Study Object: Class A Steel Truss Bridge

This study utilizes a Class A steel truss bridge with a span of 60 meters, which represents the longest span design in the Bina Marga 2005 standard [15]. The bridge consists of various structural elements connected through twelve different connection details. One of these connections will be selected for

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analysis based on its relevance to slip and yield capacity. The bridge illustration is shown in **Figure 1**.

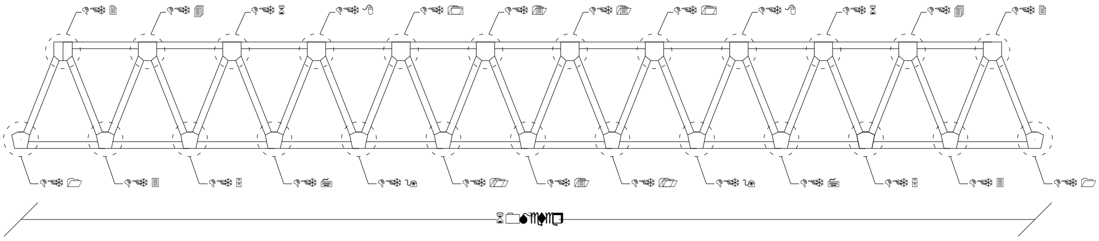

Figure 1. Class A Bridge with a 60-meter Span [15]

The bridge specifications are as follows:

Span Length	: 60 meters.
Width	: 7,00 meters.
Truss members	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Longitudinal Griders	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Plate deck	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Wind bracing members	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Other bracing members	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Connection plates	: SM 490 BJ 55 ($f_u = 550\ MPa$; $f_y = 460\ MPa$)
Bolts	: High-strength bolts JIS B 1180 Grade 8.3

This selection of the study object is expected to provide insights into the effect of bolt preload and friction coefficient on slip and yield capacity. Additionally, the study aims to generate optimal recommendations for the design of steel truss bridge connections in Indonesia.

Modeling and Simulation of Bolted Connections Using Abaqus.

The analysis is conducted on the mid-span connection, which is typically the location experiencing the highest member forces in a bridge structure. Therefore, the connection examined in this study is the upper chord connection (Detail Connection 12) of a Class A steel truss bridge with a 60-meter span, based on the Bina Marga standard [15].The selection of this connection is based on its crucial role in transmitting primary loads, making its analysis essential for gaining deeper insights into the effect of bolt preload and friction coefficient on slip and yield capacity. The detailed connection can be seen in **Figure 2**.

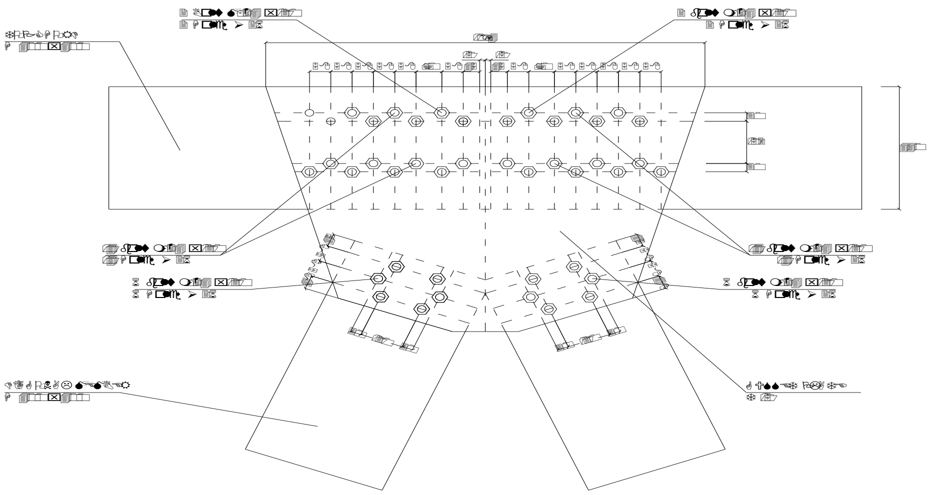

Figure 2. Detail 12: Connection of a Class A Steel Truss Bridge with a 60-Meter Span [15]

In this study, the Abaqus software is used as the primary tool for numerical analysis based on the finite element method (FEM) to evaluate the influence of bolt preload and friction coefficient on the slip and yield capacity of bolted connections in steel truss bridges. Abaqus was selected for its capability to handle nonlinear contact, complex stress analysis, and surface interaction modeling, which are crucial for simulating bolted connections. The modeling process follows the guidelines provided by Simulia Abaqus [16] to ensure that the simulation procedures adhere to best practices. In the finite element model, bolts and steel plates are represented as 3D solid elements (C3D8R) to accurately capture stress distribution. Additionally, the model is designed with high geometric tolerance to prevent mesh distortion during analysis. To improve computational efficiency, only members that directly contribute to force distribution on the connection plates are included in the simulation, while diagonal members are excluded, as they are considered to have negligible influence on the connection behavior.

The interaction between components in the Abaqus model is defined using surface-to-surface contact, with key parameters including the contact between bolts and steel plates. This interaction is governed by the hard contact method to accurately capture contact reactions. Variations in the friction coefficient are applied to analyze their effect on the slip capacity of the connection, while bolt preload is introduced as an initial condition using the bolt pretension feature. Boundary conditions are applied at both ends of the steel connection model to represent supports and external loading, as illustrated in **Figure 3**. The external load is applied as a concentrated displacement on the top chord element, simulating a loading condition under the assumption that this displacement represents the force leading to failure in the connection region. The displacement magnitude is used as a parameter to observe the connection's response until it reaches either the slip or yield limit.

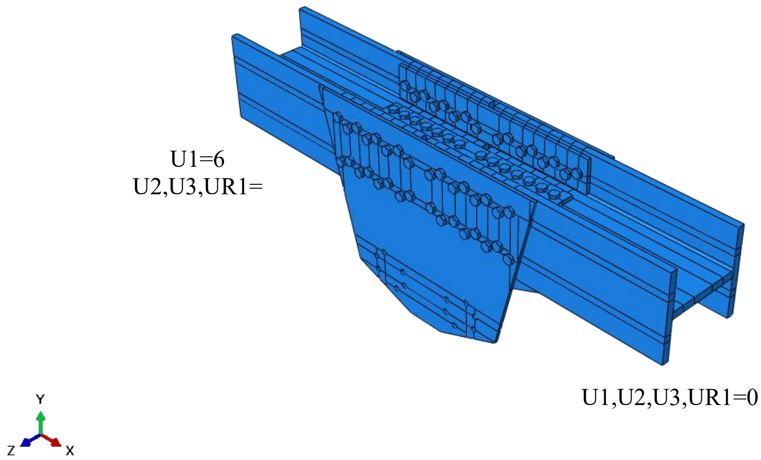

Figure 3. 3D-view and boundary conditions in the model.

To ensure the accuracy of the numerical simulation results, this study conducts validation using an analytical method based on the American Institute of Steel Construction [17]. The validation aims to compare the slip and yield capacities of bolted connections obtained from finite element simulations with analytical calculations derived from structural steel design standards. If the discrepancy between numerical results and analytical methods is within 10%, the FEM model is considered valid and can be utilized for further parametric analysis. Through this approach, the study is expected to provide deeper insights into the stress distribution within bolted connections and determine the optimal combination of preload and friction coefficient to enhance slip and yield capacity without causing premature failure in the connection.

Variations of Preload and Friction Coefficient.

The variation of preload parameters and friction coefficients aims to understand the relationship between clamping force due to preload and frictional interaction at the connection interface in determining the strength and performance of the joint. Bolt preload is the initial force applied during

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installation to enhance the connection capacity by increasing friction between the faying surfaces. In this study, preload variation is applied within a range of $0.2f_y$ to $0.9f_y$, where f_y represents the yield strength of high-strength bolts (JIS B 1180 Grade 8.8) at 640 MPa. The applied force in the modeling is calculated using Equation 1**.**

$$N = A_t\, \sigma_{bolt} \quad (1)$$

Where N is the preload force, A_t is the tensile stress area of the bolt, and σ_{bolt} is the stress in the bolt.

In addition to preload, the friction coefficient between the connection surfaces also plays a crucial role in determining the slip capacity of bolted joints. The value of the friction coefficient is influenced by the condition of the faying surfaces, which may change due to mechanical treatment, corrosion, or specific surface coatings. In this study, the friction coefficient varies between 0.30 and 0.50, representing different steel surface conditions, ranging from mill scale steel without special treatment to steel with anti-slip coatings, such as grit-based zinc coatings, as described by the American Institute of Steel Construction [17]. A total of six samples will be modeled. The variation in preload and friction coefficient values used in this study is presented in **Table 1.**

Table 1. Variation of Bolt Preload and Friction Coefficient

No	Specimen Variations	Friction Coefficient (μ)	Bolt Preload Coefficient	Preload (N)
1	fr03-1	0.3	0.2	57905.8358
2	fr03-2	0.3	0.5	144764.589
3	fr03-3	0.3	0.7	202670.425
4	fr03-4	0.3	0.9	260576.261
5	fr05-1	0.5	0.2	57905.8358
6	fr05-2	0.5	0.5	144764.589
7	fr05-3	0.5	0.7	202670.425
8	fr05-4	0.5	0.9	260576.261

Slip Capacity and Yield Analysis

The analysis is conducted in two main stages: slip capacity analysis and yield capacity analysis. The observed results include the maximum force before slip and the stress distribution around the bolts and connection plates. The slip capacity values are then compared with the analytical method based on Equation 2**.**

$$R_n = \mu\, D_u\, h_f\, T_b\, n_s \quad (2)$$

Where R_n is the slip resistance, D_u is a multiplication factor of 1.13, representing the ratio between the average installed bolt pretension and the minimum specified bolt pretension. The use of other values is allowed if recommended by the responsible engineer. The h_f factor is 1.0, acting as a filler factor used in the calculation. Additionally, T_b represents the bolt preload, while n_s indicates the number of friction surfaces contributing to the slip mechanism of the connection.

In the second stage, yield capacity analysis is performed by evaluating the stress in the bolts and plates using the Von Mises criterion (Equation 3). The yield strength of the materials used in this study is 460 MPa for SM 490 BJ 55 steel and 640 MPa for high-strength bolts. If the stress in the bolts or plates exceeds the yield strength before slip occurs, then yield failure becomes the dominant failure mechanism in the connection.

$$\sigma_{vm}= \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (3)$$

Where $\sigma_{1,}\ \sigma_2, \sigma_3$ are the principal stresses of the material.

RESULT AND DISCUSSION

Slip capcity

The slip capacity is analyzed using two approaches: analytical calculations based on the AISC standard (American Institute of Steel Construction, 2019) and numerical simulations using Abaqus. The AISC analytical calculation considers the friction coefficient (μ), bolt preload force (T_b), the number of shear planes (n_s), and the number of bolts, as expressed in Equation 2. The calculation results are summarized in **Table 2** for various specimen variations with friction coefficients of 0.3 and 0.5.

Table 2 Slip capacity calculation results based on the AISC method.

Specimen Variations	f_r	Preload (N)	Number of Installed Bolts	Slip Capacity (kN)
fr03-1	0.3	57905.836	46	1598.201
fr03-2	0.3	144764.589	46	3995.503
fr03-3	0.3	202670.425	46	5593.704
fr03-4	0.3	260576.261	46	7191.905
fr05-1	0.5	57905.836	46	2663.668
fr05-2	0.5	144764.589	46	6659.171
fr05-3	0.5	202670.425	46	9322.840
fr05-4	0.5	260576.261	46	11986.510

Slip is characterized by the relative displacement between two connected elements due to shear force exceeding the frictional force at the contact interface of the connection. Once slip occurs, the connected elements may shift until reaching a new stable position or continue to deform, depending on the loading conditions and connection design. **Figure 4** shows that the slip capacity (initial relative displacement at slip) occurs at the following loads: 1549.070 kN for specimen fr03-1, 3938.860 kN for fr03-2, 5563.820 kN for fr03-3, 7179.510 kN for fr03-4, 2648.830 kN for fr05-1, 6639.030 kN for fr05-2, 9187.760 kN for fr05-3, and 11354.100 kN for fr05-4.

The slip mechanism in bolted connections consists of two phases. The first phase occurs when the shear force is entirely resisted by friction between the contact surfaces, which depends on the bolt preload and the friction coefficient. Slip initiates once the shear force exceeds this frictional resistance. The second phase begins when shear resistance is no longer solely governed by friction but also involves the bearing mechanism, where the bolt comes into contact with the edge of the main plate hole. Simulation results indicate that only specimens fr03-1, fr03-2, and fr05-1 experience both slip phases, while the other specimens exhibit only a single-phase slip (**Figure 4**). The initial slip phase is represented by a linear increase in the shear force versus displacement graph, indicating bolt movement after the shear force surpasses the frictional resistance between steel surfaces. The first contact between the bolt and the hole edge marks the onset of the bearing mechanism (**Figure 5**). The second slip phase occurs when the shear force continues to increase, leading to further relative displacement until the bolt makes contact with the gusset plate (**Figure 6**). These findings suggest that the number of slip phases is significantly influenced by the connection configuration and design parameters.

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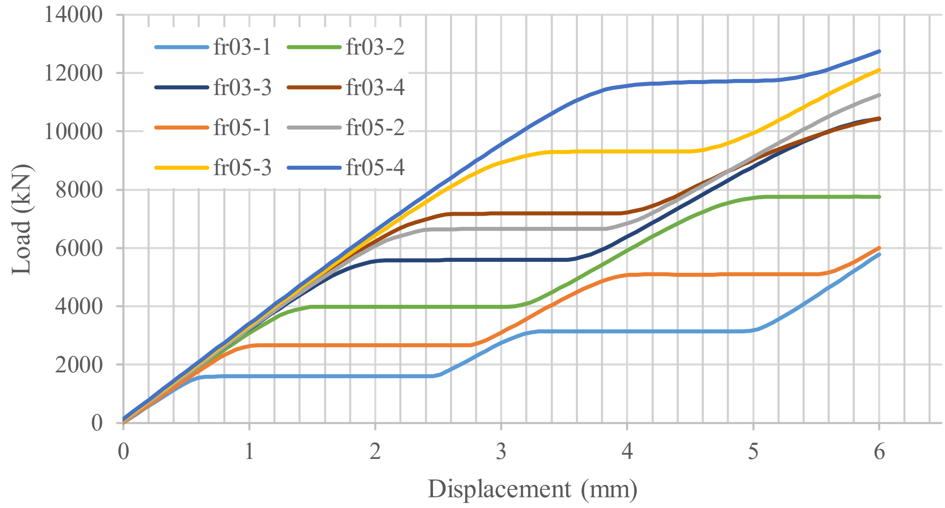

Figure 4. Load vs displacement

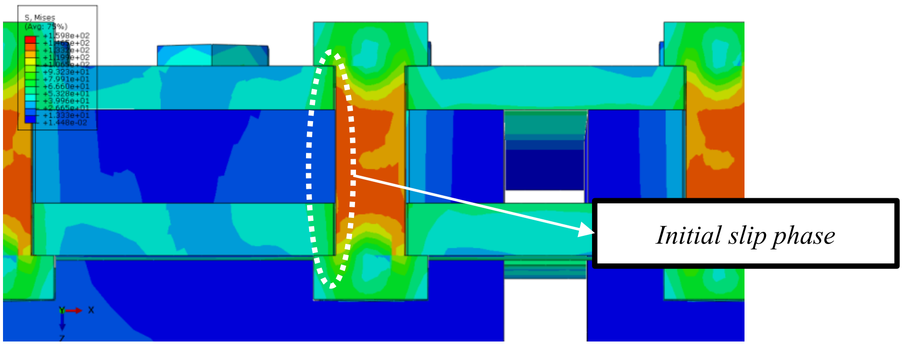

Figure 5. Initial slip phase

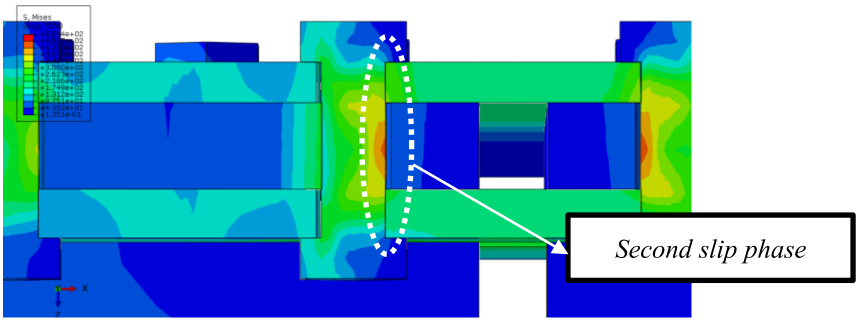

Figure 6. Second slip phase

Table 3 and **Figure 7** indicate that the difference between the slip capacity analysis results using the analytical AISC method and the Abaqus simulation is relatively small, with an average error of 1.6%. This demonstrates that both methods validate each other, making the simulation results reliable for further analysis. Therefore, in this study, the slip capacity values used for further analysis are derived from the Abaqus simulation.

Table 3. Comparison of slip capacity between the AISC method and Abaqus

Specimen Variations	f_r	Preload (N)	Slip Capacity (kN)		Error
			AISC	Abaqus	
fr03-1	0.3	57905.836	1598.201	1549.070	3.07%
fr03-2	0.3	144764.589	3995.503	3938.860	1.42%
fr03-3	0.3	202670.425	5593.704	5563.820	0.53%
fr03-4	0.3	260576.261	7191.905	7179.510	0.17%
fr05-1	0.5	57905.836	2663.668	2648.830	0.56%
fr05-2	0.5	144764.589	6659.171	6639.030	0.30%
fr05-3	0.5	202670.425	9322.840	9187.760	1.45%
fr05-4	0.5	260576.261	11986.508	11354.100	5.28%

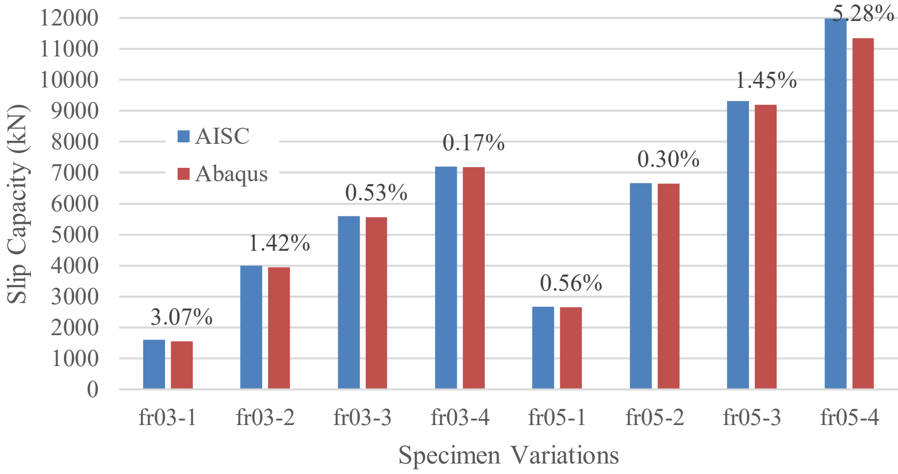

Figure 7. Comparison of slip capacity using the AISC method and Abaqus.

The analysis results indicate that at lower friction coefficient values, the connection experiences slip at lower shear loads. This suggests that smoother bolt surfaces reduce the shear strength of the connection, as the lower frictional force is insufficient to resist higher shear forces before slip occurs. Conversely, with an increased friction coefficient, the connection can withstand higher shear loads before slipping. This demonstrates that rougher connection surfaces or specially treated surfaces, such as anti-slip coatings, can enhance the connection's resistance to displacement.

The analysis of the relationship between bolt preload and slip capacity for two different friction coefficient values, 0.3 and 0.5, is presented in **Figure 8**. In general, slip capacity increases linearly with increasing bolt preload for both friction coefficient values. The results indicate that the slip capacity for a friction coefficient of 0.5 is consistently higher than that for 0.3, confirming that a higher friction coefficient contributes to an increase in the slip capacity of bolted connections. Additionally, the percentage increase in slip capacity is more significant at the initial preload range, reaching 154% for a friction coefficient of 0.3 and 151% for 0.5, compared to the final range, which only reaches 29% and 24%, respectively. This suggests that the influence of increasing preload on slip capacity tends to diminish at higher preload values, making preload enhancement more effective within the low to moderate preload range. Meanwhile, the relationship between the friction coefficient and slip capacity for different preload variations is presented in **Figure 9**, where the average increase in slip capacity due to a higher friction coefficient reaches 65.71%. These results indicate that the friction coefficient has a significant and consistent impact on enhancing slip capacity across all preload variations.

The findings of this study are consistent with previous research [4], which demonstrated that slip capacity increased by 35.71% when the preload was raised from 0.53 f_y to 0.72f_y. Additionally, the

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influence of slip factors on slip capacity is evident, as an increase in the friction coefficient from 0.31 to 0.55 resulted in a 77.42% rise in slip capacity. According to the AISC [17] methodology, increasing the preload from $0.5f_y$ to $0.7f_y$ enhances slip capacity by 28.57%, while raising the friction coefficient from 0.3 to 0.5 leads to a 66.67% increase in slip capacity.

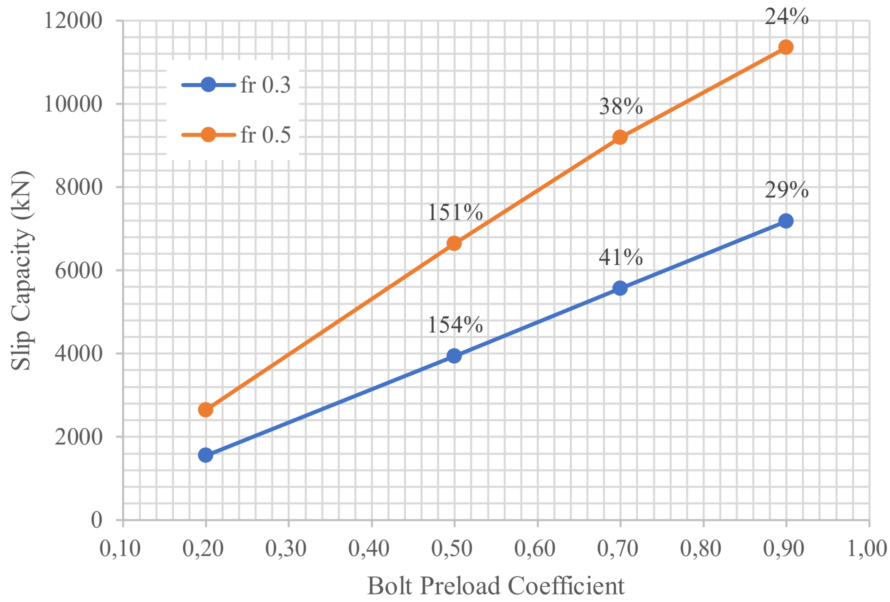

Figure 8. Effect of preload on slip capacity

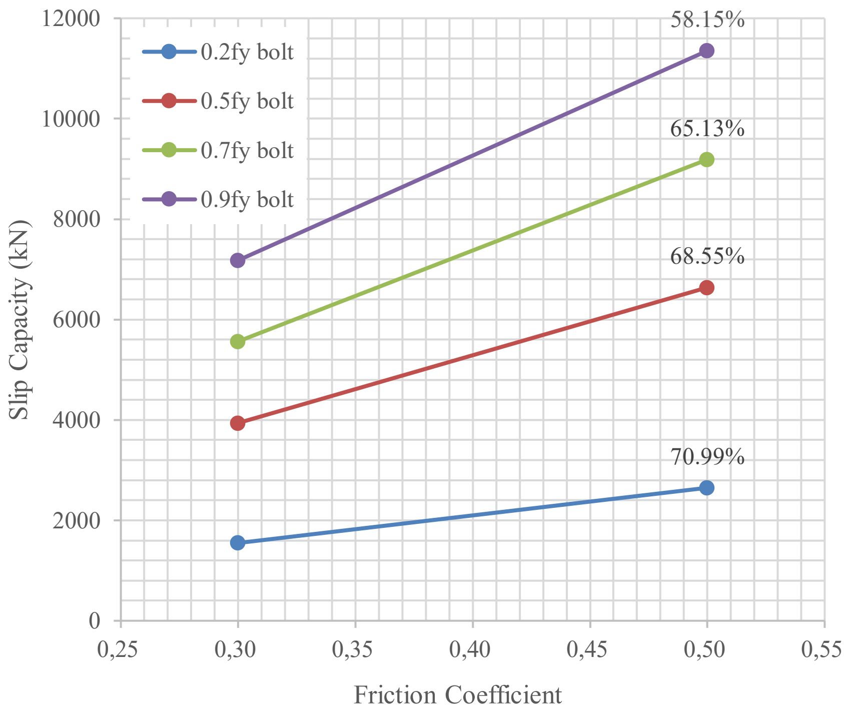

Figure 9. Effect of Friction Coefficient on Slip Capacity

Yield Capacity

The analysis results indicate a shift in the location of stress concentration on the gusset plate of the connection as the load increases, as shown in **Figure 11, Figure 10,** and **Figure 12.** This displacement is attributed to variations in load distribution, changes in plate stiffness due to deformation, and the influence of bolt preload, which causes stress redistribution around the bolt holes—key points of force interaction and deformation.

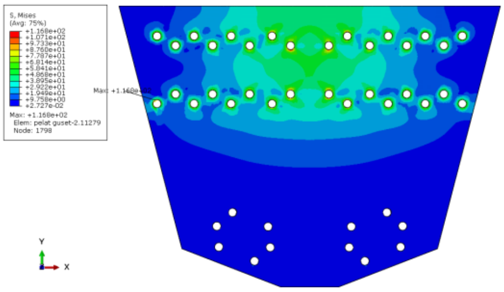

Figure 11 Stress concentration at location 1.

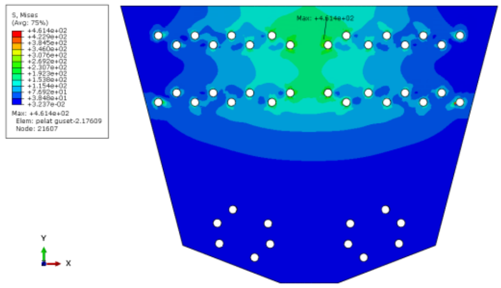

Figure 10. Stress concentration at location 2.

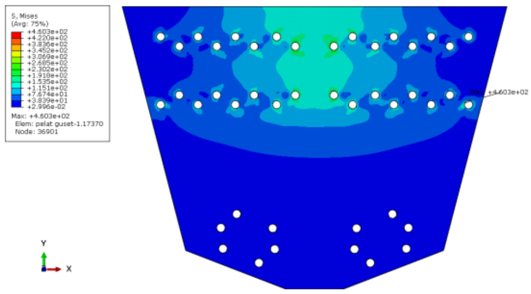

Figure 12. Stress concentration at location 3.

The stress distribution in various specimens indicates that material failure initially occurs in specimen fr03-1 at location 3 with a capacity of 4244.060 kN, in specimen fr03-2 at location 2 with a capacity of 6649.790 kN, in specimen fr03-3 at location 1 with a capacity of 6005.900 kN, in specimen fr05-1 at location 3 with a capacity of 5706.270 kN, in specimen fr05-2 at location 2 with a capacity of 7457.870 kN, and in specimen fr05-3 at location 2 with a capacity of 8707.030 kN, as shown in **Figures 13, Figures 14, Figures 15, Figures 16, Figures 17, Figures 18, Figures 19** and **Figures 20**. Meanwhile, specimens fr03-4 and fr05-4 experienced material failure prior to the application of rod load due to bolt preload causing the von Mises stress (σ_{vm}) to exceed the yield strength (f_y) of the gusset plate.

Furthermore, the analysis of the force-deformation relationship graph reveals a break in the curve, indicating a transition from a stable condition to a slip condition where the frictional force is no longer sufficient to resist the relative displacement between the connected surfaces. This phenomenon is critical in the design of steel connections, as slip can affect the strength and stability of the structure, and therefore must be carefully addressed to prevent structural failure.

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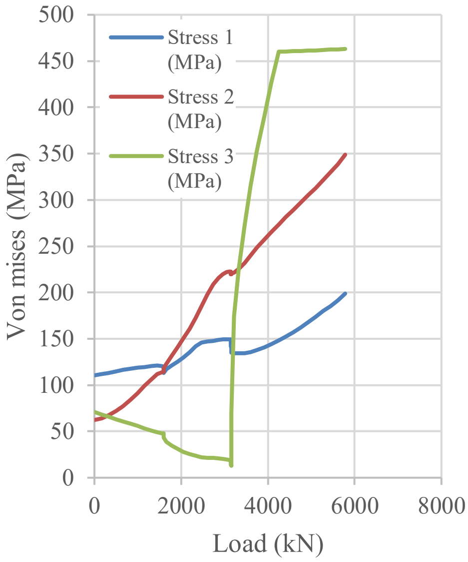

Figure 13. Von Mises stress (fr03-1).

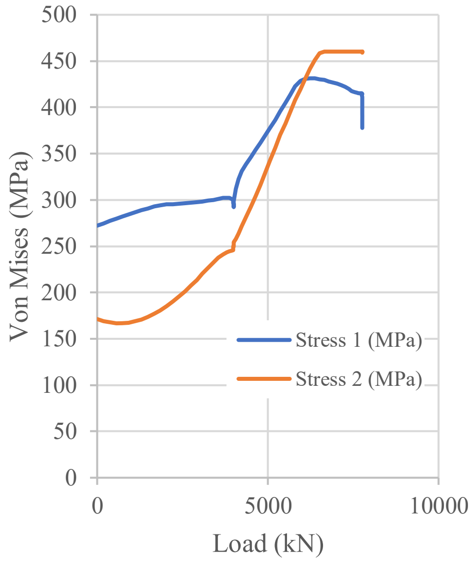

Figure 14 Von Mises stress (fr03-2)

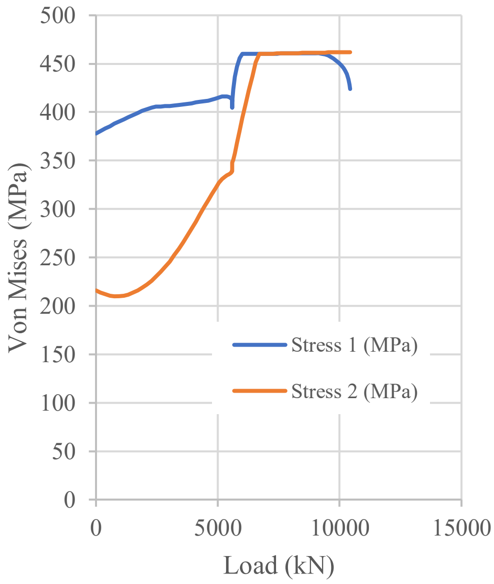

Figure 15. Von Mises stress (fr03-3).

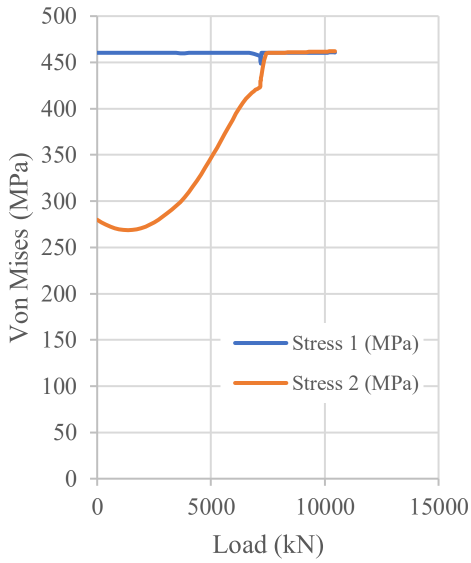

Figure 16. Von Mises stress (fr03-4).

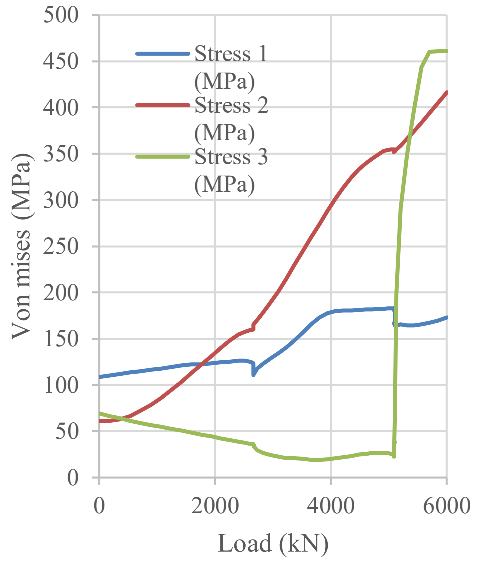

Figure 17. Von Mises stress (fr05-1).

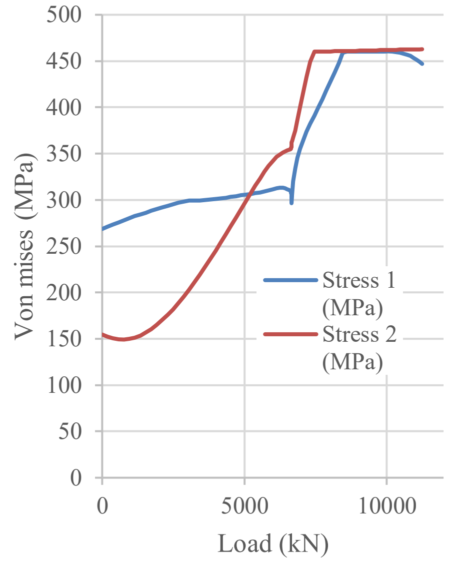

Figure 18. Von Mises stress (fr05-2).

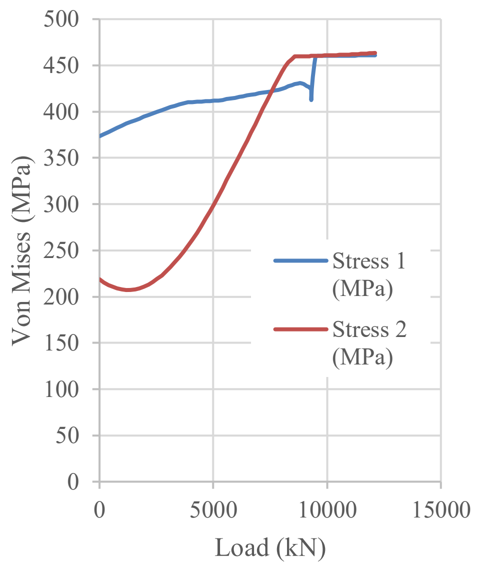

Figure 19. Von Mises stress (fr05-3).

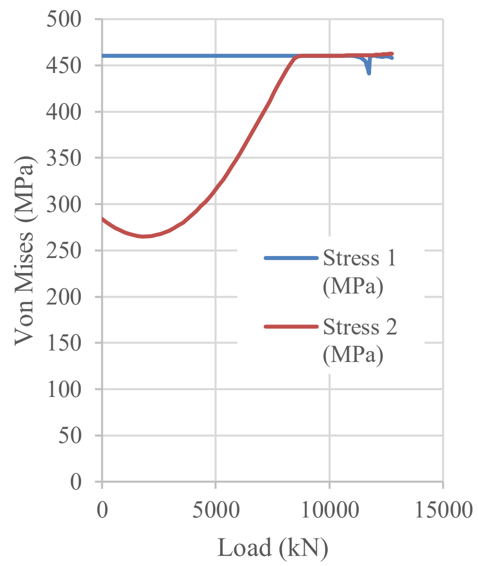

Figure 20. Von Mises stress (fr05-4).

The yield capacity analysis results indicate that preload can enhance bolt capacity up to failure by 17.30% to 31.43% at a friction coefficient of 0.5 and even up to 50% at a friction coefficient of 0.3, as shown in **Figure 21**. These findings align with the study conducted by Lyu et al. (2021), which demonstrated that bolt preload significantly increases the total failure capacity of high-strength steel connections by 15% to 29% compared to connections without preload. Additionally, the results indicate that the lower the friction coefficient, the greater the influence of preload on connection capacity, meaning that higher preload application is more effective for connections with low friction. Therefore, optimizing the balance between preload and friction coefficient is necessary to achieve more efficient connections, as illustrated in **Figure 21** and **Figure 22**. The friction coefficient plays a crucial role in enhancing the yield capacity of bolted connections, but its effect diminishes at extremely high preload levels, where excessive preload may cause localized failure due to nut pressure around the bolt hole. The yield capacity recap for each specimen is presented in **Table 4**,

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showing that the highest yield capacity is achieved in specimen fr05-3, with a value of 8,585.490 kN, while specimens fr03-4 and fr05-4 failed before the main member force was applied.

Table 4. The yield capacity for each specimen variation

Specimen Variations	Yield Capacity (kN)
fr03-1	4412.460
fr03-2	6649.790
fr03-3	6005.300
fr03-4	0.000
fr05-1	5568.870
fr05-2	7319.170
fr05-3	8585.490
fr05-4	0.000

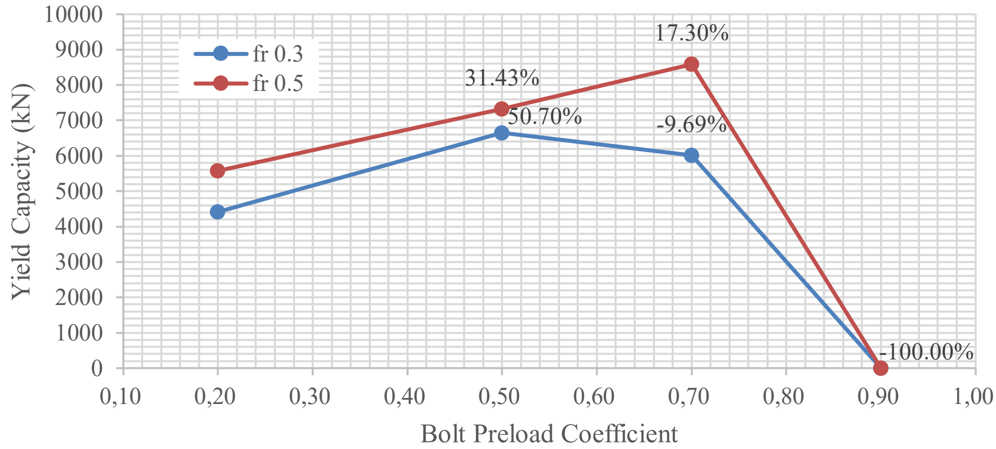

Figure 21. Effect of preload on yield capacity

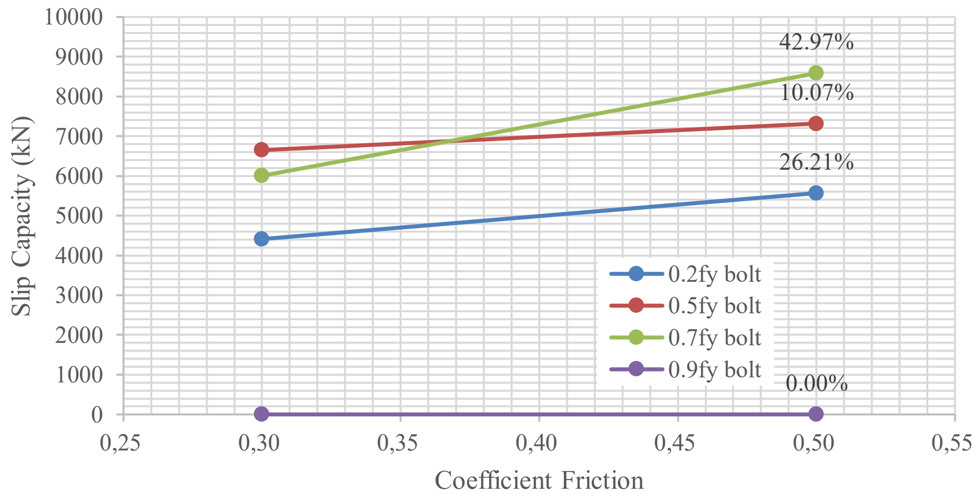

Figure 22. Effect of friction coefficient on yield capacity.

Combination of Slip and Yield Failure

The bridge capacity is analyzed based on two failure mechanisms: slip and yield. The connection capacity is evaluated from the condition where either of these mechanisms occurs first. At a friction coefficient of 0.3, all preload variations experience slip failure before yielding occurs. However, at a friction coefficient of 0.5, slip failure occurs first for preload variations below $0.7f_y\ bolt$, whereas for preload variations exceeding $0.7f_y\ bolt$, local material failure occurs before slip. This indicates that connection failure is not solely dependent on a single mechanism; instead, both mechanisms can occur either simultaneously or separately, depending on the loading conditions and material properties of the connection. The simulation results suggest that the optimum preload is at $0.7f_y\ bolt$ and the influence of friction coefficient and preload on slip capacity is mutually supportive. A summary of the capacity comparison is presented in **Table 5**.

Table 5. Optimization of preload and friction coefficient based on slip and yield capacity.

Specimen Variations	f_r	Preload (MPa)	Yield Capacity (kN)	Slip Capacity (kN)	Description
fr03-1	0.3	0.20	4412.460	1549.070	Slip
fr03-2	0.3	0.50	6649.790	3938.860	Slip
fr03-3	0.3	0.70	6005.300	5563.820	Slip
fr03-3	0.3	0.90	0.000	7179.510	Yield
fr05-1	0.5	0.20	5568.870	2648.830	Slip
fr05-2	0.5	0.50	7319.170	6639.030	Slip
fr05-3	0.5	0.70	8585.490	9187.760	Yield
fr05-4	0.5	0.90	0.000	11354.100	Yield

CONCLUSION

Based on the results of this study, it can be concluded that the slip capacity of the connection increases with higher preload and friction coefficient. At a low friction coefficient (0.3), slip occurs at a load ranging from 1549.07 kN (preload $0.2f_y$) to 7179.51 kN (preload $0.9f_y$), whereas at a high friction coefficient (0.5), slip occurs at an initial load of 2648.83 kN (preload $0.2f_y$) to 11354.1 kN (preload $0.9f_y$). The slip mechanism in bolted connections consists of two phases. The first phase occurs when the shear force is fully resisted by the friction between the faying surfaces until it reaches its capacity limit. The second phase occurs when the bolts begin to make contact with the sides of the main member holes and gusset plate, involving bearing contribution. The number of slip phases depends on the connection conditions and design parameters, where specimens fr03-1, fr03-2, and fr05-1 exhibit two slip phases, while the other specimens experience only one slip phase. Validation between the AISC analytical method and Abaqus simulation shows an average result difference of 1.6%, with a maximum error of 5.28% in specimen fr05-4. Bolt preload and friction coefficient have been proven to significantly increase the yield capacity of the connection. At a high friction coefficient (0.5), the yield capacity increases by 31.43% at preload $0.5f_y$ and 17.30% at preload $0.7f_y$, whereas at a low friction coefficient (0.3), the increase reaches 50% at preload $0.5f_y$. This also indicates that the lower the friction coefficient, the greater the influence of preload on connection capacity. Von Mises stress distribution shows that material failure first occurs in the gusset plate area, where preload $0.2f_y$ results in a yield capacity of 4412.46 kN for a friction coefficient of 0.3 and 5568.87 kN for a friction coefficient of 0.5. At preload $0.5f_y$, the yield capacity increases to 6649.79 kN (friction coefficient 0.3) and 7319.17 kN (friction coefficient 0.5), while at preload $0.7f_y$, the yield capacity reaches 6005.30 kN (friction coefficient 0.3) and 8585.49 kN (friction coefficient 0.5). However, at preload $0.9f_y$, there is a drastic decrease in yield capacity, even reaching zero for both friction coefficients (0.3 and 0.5). This indicates that excessively high preload may cause local failure in the connection due to stress concentration around the bolt holes. Therefore, connection design must consider the balance between preload and friction coefficient to optimize connection capacity while avoiding local failure risks. The optimum preload for different friction coefficient variations is determined based on the specimen that achieves maximum connection capacity before experiencing premature failure (slip or yield). From the study results, the optimum preload is $0.7f_y$, where the connection capacity for a friction coefficient of 0.3 is 5563.82 kN, and for a friction coefficient of 0.5, it is 8585.49 kN.

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