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ELABORATE FINITE ELEMENT MODEL FOR RESILIENT SLIP FRICTION JOINTS

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ABSTRACT

Resilient Slip Friction Joints (RSFJs) have emerged as an effective solution for achieving energy dissipation and self-centering capabilities in seismic-resistant structural systems. This study presents the development and validation of a finite element (FE) model for simulating the mechanical behavior of RSFJs. ABAQUS/CAE 2020 was employed to develop the proposed model, which is based on steel plates sliding over each other and connected by pretensioned bolts and elastic springs. The proposed modeling approach enables accurate prediction of key connection parameters, providing a reliable numerical framework for analyzing the performance of RSFJs.

The FE model validation was carried out through comparison with both experimental results and, analytical equations. The comparison focused on the hysteresis curve characteristics, with particular emphasis on the force corresponding to maximum allowable relative displacement, stiffness, and the level of damping. In addition, the FE model was employed to perform a comprehensive parametric study aimed at assessing the effects of key design parameters including spring stiffness, bolt pre-tension force, and friction coefficient on the overall performance of the joint.

KEYWORDS

Resilient Slip Friction Joint;
Finite element model;
Seismic-resistant systems;
Self-centering;
Energy dissipation.

1. INTRODUCTION

The Resilient Slip Friction Joint (RSFJ) is a damage-avoidance friction damper that integrates both energy dissipation and self-centering capabilities within a single, compact device. This performance is achieved through controlled frictional sliding between specially grooved steel plates engineered to withstand the induced tension,

bending, and shear forces while remaining fully elastic, as required by the damage-avoidance design philosophy. Fig. 1 shows the components and the assembly of the Resilient Slip Friction joint.



Fig. 1 components and assembly of RSFJ

The load-displacement response of the RSFJ exhibits the characteristic flag-shaped behavior associated with self-centering systems possessing energy dissipation capability. Fig.2 illustrates the flag-shaped hysteretic response of a RSFJ with the explained forces and displacements. According to the graph, upon loading, the initial static frictional resistance between the clamped grooved surfaces is overcome and the joint starts opening up; the corresponding external force on the joint is called the slipping force (F_{slip}). With continued loading and progressive joint opening, energy is dissipated through the sliding friction mechanism and disc springs situated at the top and the bottom of the joint until the disc springs become fully compressed and locked, this is the ultimate state of the device and the corresponding external force on the joint is called the ultimate force (F_{ult}). Upon release of the external force, the combined effect of the spring stiffness and the bolt pretension force generates a restoring action that drives the joint to reverse its direction of motion and move back toward its original position; the corresponding external load is termed the restoring force (F_{rest}). Finally, the minimum force immediately prior to the joint returning to its initial position is defined as the residual force (F_{resid}). Furthermore, the enclosed area within the hysteretic loops representing the absorbed energy increases steadily with increasing joint deformation, this indicates enhanced energy absorption through friction and clearly demonstrates the damage-avoidance behavior of the RSFJ, as the joint maintains its stiffness and strength over repeated loading and unloading cycles.

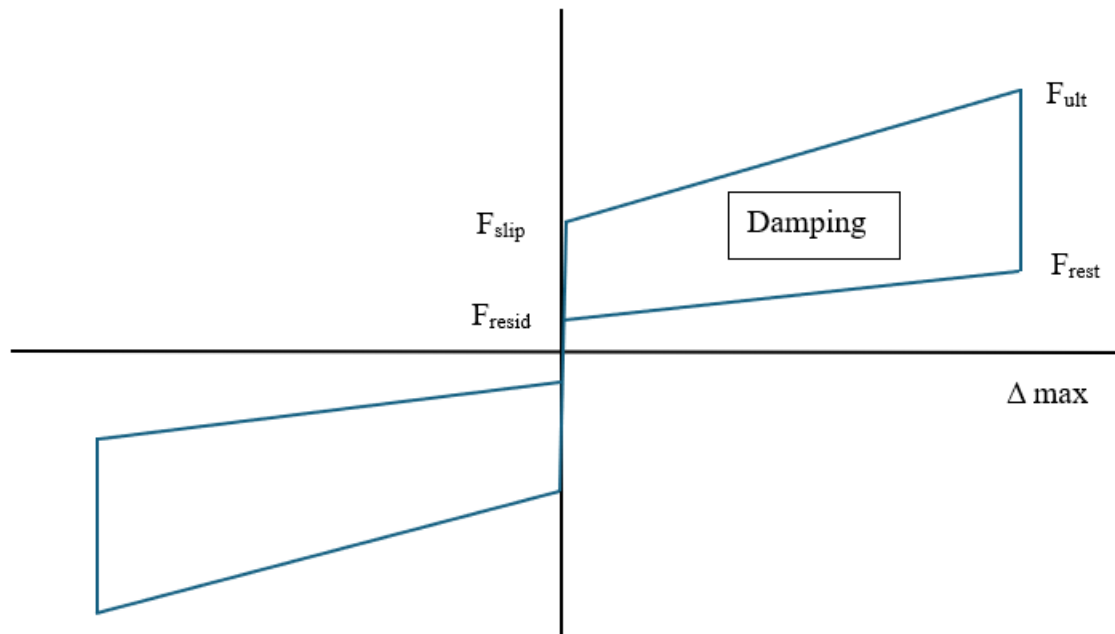


Fig. 2 Schematic force - displacements loop for the RSFJ.

Resilient Slip Friction Joint (RSFJ) was developed in New Zealand following the Christchurch earthquakes [1] by Zarnani and Quenneville (2015) to address the issue of residual displacements in structures after major seismic events, while simultaneously providing energy dissipation within a single device [2].

The joint has been experimentally investigated, where its characteristic flag-shaped hysteretic response and governing equations have been validated in previous studies [3] Furthermore, both the in-plane and out-of-plane rotational behavior of the joint, along with the corresponding analytical formulations, were examined [4]

The Resilient Slip Friction Joint (RSFJ) has been widely evaluated across different steel structural systems, including tension-only braces [5], tension–compression braces [6], and steel moment-resisting frames [7]. Recent shake-table experiments conducted on a three-story steel structure have further demonstrated the effectiveness of the RSFJ in achieving reliable self-centering behavior while maintaining a uniform deflection profile [8].

Beyond steel systems, RSFJs have also been successfully applied in a range of other structural configurations. Notably, they have been utilized as hold-down devices in rocking timber shear walls [9] and have more recently been extended to precast concrete shear walls [10], where they contribute to enhanced self-centering capability and improved energy dissipation performance. More recently, a rotational form of the RSFJ has been developed to enhance displacement capacity [11], which has subsequently been applied in rocking concrete shear wall systems [12].

2. FINITE ELEMENT MODEL FOR RSFJ

Experimental testing of structural connections such as the (RSFJ) is often challenging due to the high costs, specialized equipment, and complex loading protocols required to accurately simulate seismic demands. In addition, full-scale testing is time-consuming and typically limited to a narrow range of configurations, making it difficult to explore the broad parameter space needed for design optimization. Therefore, the use of advanced finite element (FE) modeling programs has become essential. FE analysis provides a powerful and efficient means to replicate the nonlinear, frictional, and self-centering behavior of the joint, enabling detailed investigations of its performance under various loading scenarios.

In this study, the finite element software [13] was employed to develop a detailed numerical model of the connection. The numerical results obtained from the ABAQUS simulations were validated through comparison with an experimental study reported in [9]. In addition, a separate numerical model was established and its results were compared with the analytical equations presented in [9] to further assess the accuracy and reliability of the proposed modeling approach.

2.1 ABAQUS MODEL VS EXPERIMENTAL STUDY.

Hashemi et al.2017[9]. conducted experimental investigations to evaluate the behavior of the RSFJ. The results experimentally confirmed that this joint is able to provide a self-centering behavior in addition to a significant rate of seismic energy dissipation through friction. Fig3-1 shows the configuration of the tested RSFJ.

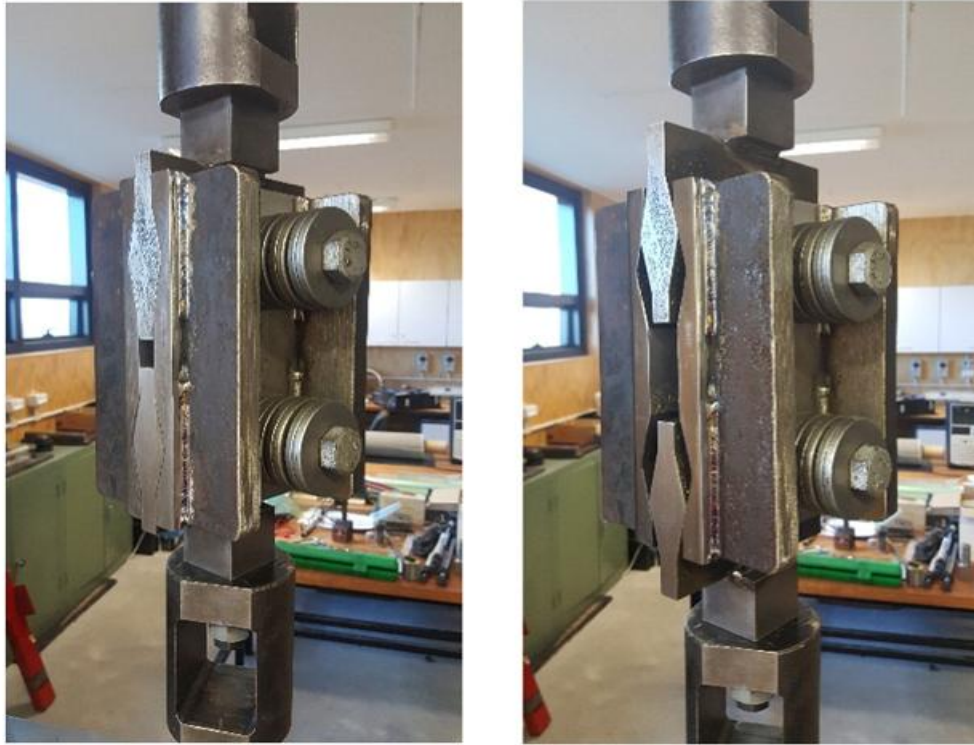


Fig3-1 tested RSFJ, Hashemi et al. 2017.

2.1.1 DESIGN PARAMETERS.

Table-1 Shows the basic parameters values used in test.

Parameter	Value
Steel grade	350
Bolts grade	8.8
number of the bolts on each splice (n_b)	1
angle of the grooves (θ)	15°
coefficient of friction (μ_s)	0.19
Target displacement(mm)	30
Belleville spring capacity(kN)	110
Belleville spring overall height(mm)	8
Belleville spring internal height(mm)	1.5
Number of the springs per bolt	18

Table-1 test parameters value

Regarding Belleville Spring discs, they are replaced in the FE model with elastic springs, 8 springs for each bolt side connected between the movable washer and the bolt nut in order to simplify the model. An image from the ABAQUS/CAE 3D finite element model is displayed in Fig3-2

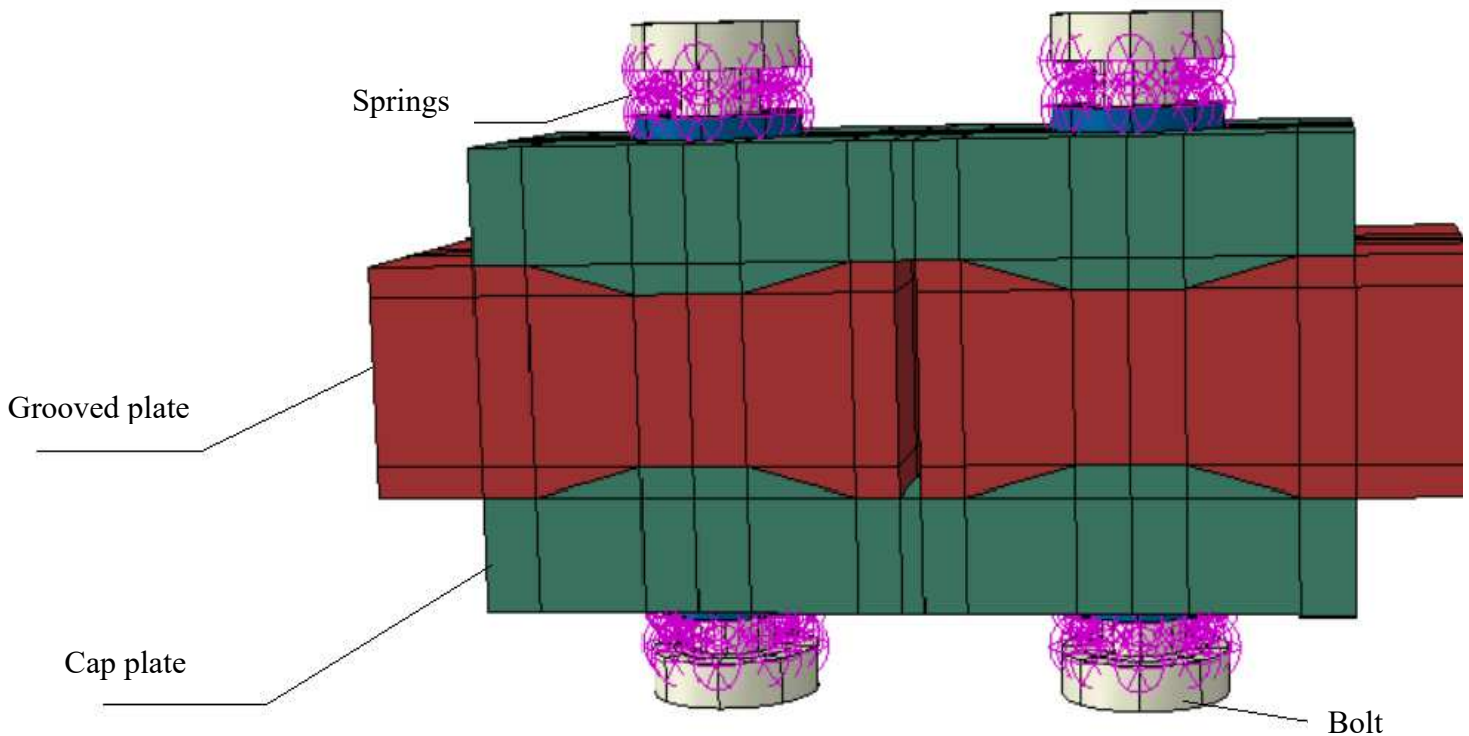


Fig3-2 RSFJ 3D finite element model.

2.1.2 MATERIAL PROPERTIES.

The constitutive model of steel is designed using the bi linear elastic plastic material. The steel has a Poisson's ratio of 0.3, mass Density = 7.85 t/m^3 , elastic modulus "Es" = 2100 t/cm^2 and yield stress = 350 N/mm^2 for plates and 640 N/mm^2 for bolts. all these factors are taken in consideration in ABAQUS CAE software.

2.1.3 MODEL MESHING.

A series of mesh refinement studies was conducted to assess the sensitivity of the results to various mesh shapes and to determine an appropriate mesh size for performing the finite element analysis. All parts are simulated using a three-dimensional 8 node solid element with reduced integration (C3D8R). Element mesh size of 10 mm for cap plates, grooved plate and bolts are used in the present FE model. The movable washers are modelled with fine mesh size of 5 mm for better simulation of stress concentration region. Fig3-3 shows the Meshing technique for the joint.

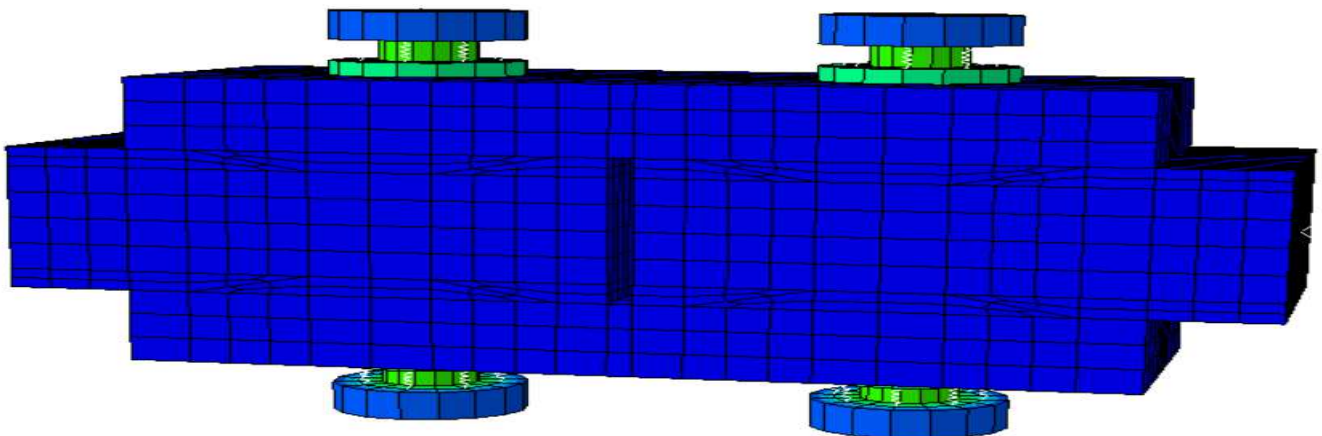


Fig3-3 Meshing technique for FE model.

2-1-4 INTERACTIONS.

For the normal behavior (hard contact) which allows separation after contact is used. while for the tangential behavior (penalty friction formulation), which simulates frictional behavior that resists tangential relative motion between contacting surfaces, is used. A friction coefficient of 0.19 was adopted, which is lower than the typical friction coefficient for steel-to-steel contact. However, in this case, the reduction is justified because, proper lubrication is essential for preventing galling, minimizing surface scratches, and ensuring long-term performance of the plates. All contact surfaces are coated with a specialized grease prior to assembling the RSFJ. This lubrication not only enhances the hysteretic behavior of the connection but also helps reduce residual drift.

2-1-5 BOUNDARY CONDITIONS AND LOADING.

For the boundary conditions, a reference point (RP-L) was assigned to the left end face of the slotted plate, and its movement was restricted in Y and Z directions also, rotation was restricted in X, Y and Z-directions. Similarly, another reference point (RP-R) was connected to the right end face under the same constraints. Regarding loads, the first step involved applying a uniform pre-tension force at the mid-level of each bolt shank (Fig3-4a). In the followed step, a displacement condition was applied to both ends in opposite directions (Fig3-4b). A specific amplitude curve was defined for this loading, starting from zero and increasing to 100% of the target displacement, followed by a return to zero to represent the unloading phase. A geometric nonlinear analysis was carried out to obtain the force displacement response of the RSFJ. The analysis was conducted using Newton Raphson equation solver with automatic stepping.

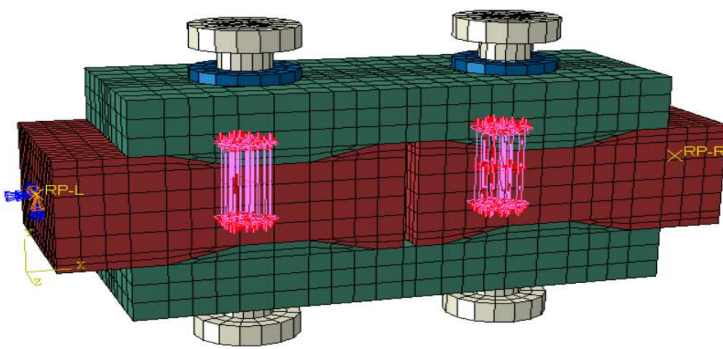


Fig3-4a pre-tension force fore bolts

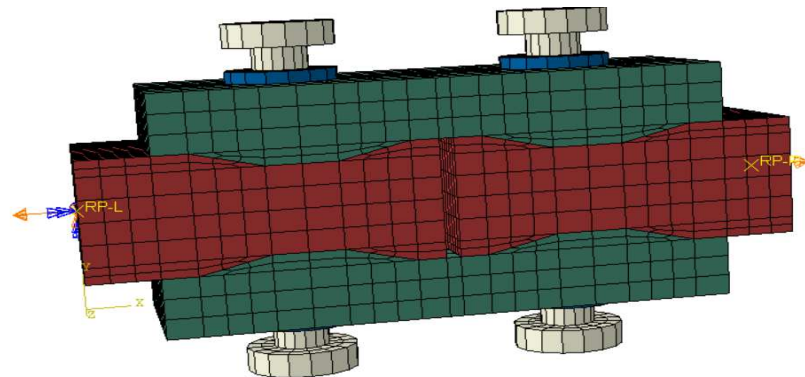


Fig3-4b displacement at both ends

2.1.6 ANALYSIS RESULTS.

As shown in Fig3-5, the force–displacement response of the RSFJ exhibits flag-shaped hysteretic curve, which indicates pronounced self-centering behavior accompanied by significant energy dissipation. It is apparent that the enclosed area within the hysteresis loops, representing the dissipated energy, increases at a nearly constant rate. In other words, as joint deformation increases, the amount of energy absorbed through friction also increases, clearly demonstrating a damage-avoidant response. This behavior is attributed to the joint's ability to retain its stiffness and strength over loading and unloading cycles.

Furthermore, the finite element model indicates that, the maximum stress is below the capacity of the plates, no buckling or yielding occurred in any of the modeled components. Fig3-6 shows Stress contour in the connection

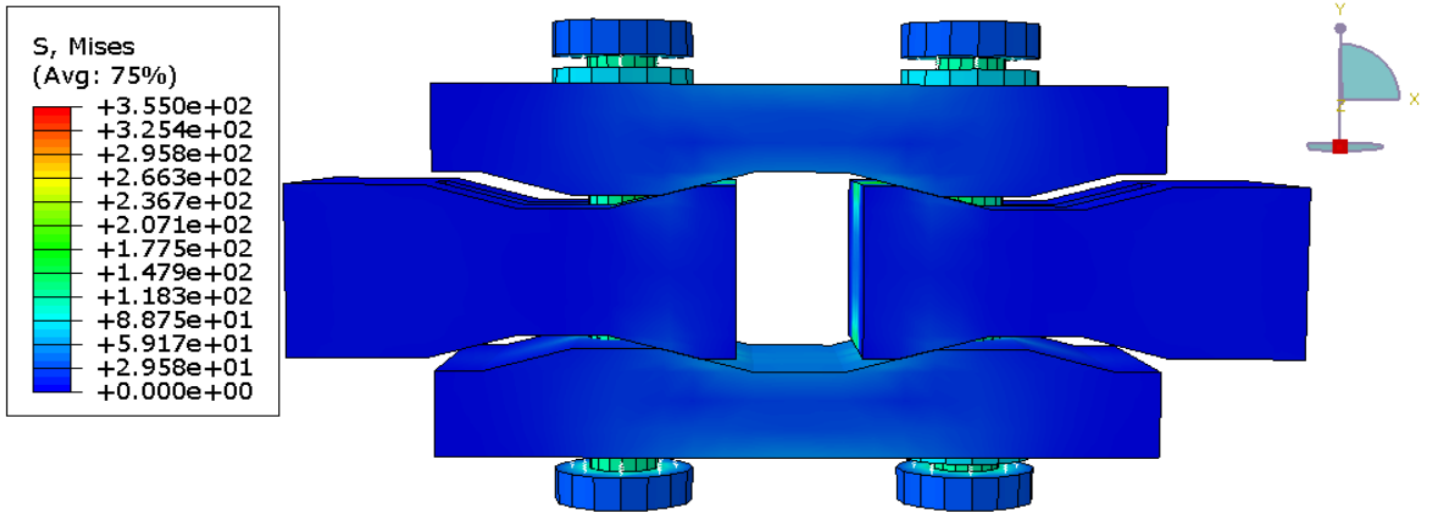


Fig3-6 Stress contour in the connection

2.1.7 MODEL VERIFICATIONS.

The force-displacement curve of the RSFJ obtained from ABAQUS compared with experimental curve presented in Fig 3-5. The finite element model accurately captured the hysteretic behavior of the RSFJ. The existing discrepancies between the finite element results and the experimental results regarding the unloading stiffness may arise from several factors, including the minor scratches on the plate surfaces, as well as the uneven surface conditions of the plates in the experimental setup.

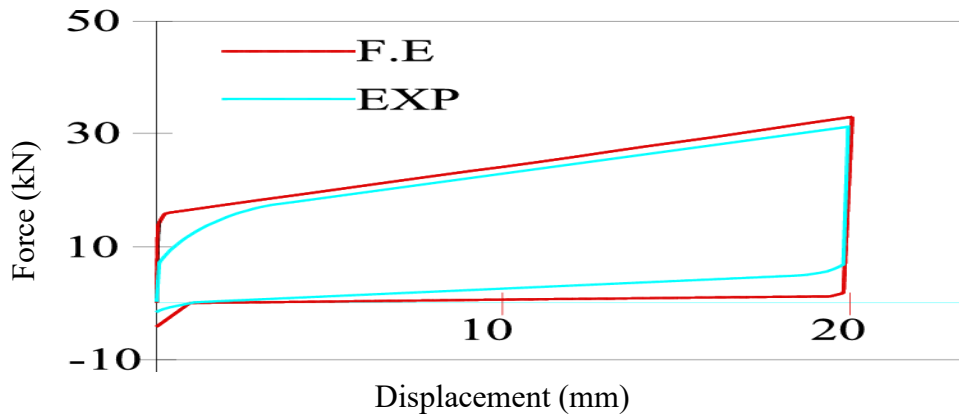


Fig 3-5 Hysteretic behavior for FE model compared with the Experimental test result.

From the analysis of the force-displacement curve of the RSFJ, it can be inferred that the slope of the initial segment represents the Initial stiffness (K_0) of the joint before slip occurs, which is notably high and can therefore be considered a fully restrained connection. The second stiffness (k_1) reflects the joint stiffness during the loading phase. The area included in the flag shaped curve represents the amount of energy absorbed by the joint. All these factors, in addition to the sliding and ultimate forces, were taken into account in the comparative analysis, as summarized in table-2.

	EXP	FE model	EXP/FE
F_{slip} (kN)	15	15.7	0.96

F _{ult} (kN)	30	32.9	0.92
K1 (kN/mm)	0.75	0.86	0.88
Damping	420	470	0.9

Table-2 The experimental test result compared with the FE model

2.2 ABAQUS MODEL VS ANALATYICAL EQUATIONS.

For further validation, an additional verification model was conducted to assess the efficiency of the finite element model, this time by comparing it with the analytical equations developed in [9].

$$F_{\text{slip}} = 2 n_b F_{b,\text{pr}} \left(\frac{\sin \theta + \mu_s \cos \theta}{\cos \theta - \mu_s \sin \theta} \right) \quad (1)$$

$$F_{\text{ult}} = 2 n_b F_{b,\text{ult}} \left(\frac{\sin \theta + \mu_k \cos \theta}{\cos \theta - \mu_k \sin \theta} \right) \quad (2)$$

$$F_{\text{rest}} = 2 n_b F_{b,\text{ult}} \left(\frac{\sin \theta - \mu_k \cos \theta}{\cos \theta + \mu_k \sin \theta} \right) \quad (3)$$

$$F_{\text{resid}} = 2 n_b F_{b,\text{pr}} \left(\frac{\sin \theta - \mu_k \cos \theta}{\cos \theta + \mu_k \sin \theta} \right) \quad (4)$$

2.2.1 DESIGN ASSUMPTIONS.

By assuming that, number of bolts(n_b)=1, angle of the grooves $\theta=15^\circ$, friction coef. $\mu=0.18$, the pre-stressing force of each bolt ($F_{b,\text{pr}}$)=30.0 kN, springs stiffness k_s & max. relative displacement Δs are 14.0 kN/mm & 30mm respectively. It should be noted that all previous FE procedure, including material classification, meshing techniques, and boundary conditions were applied to this model as well.

2.2.2 COMPARISON OF RESULTS.

Fig3-7 & Table-3 shows a comparison between results from the analytical equations and the FE model. the comparison clearly demonstrates a good agreement between the numerical results obtained from ABAQUS and those predicted by the analytical equations. Accordingly, it can be concluded that, the developed FE model provides a reliable tool for estimating the behavior of the RSFJ.

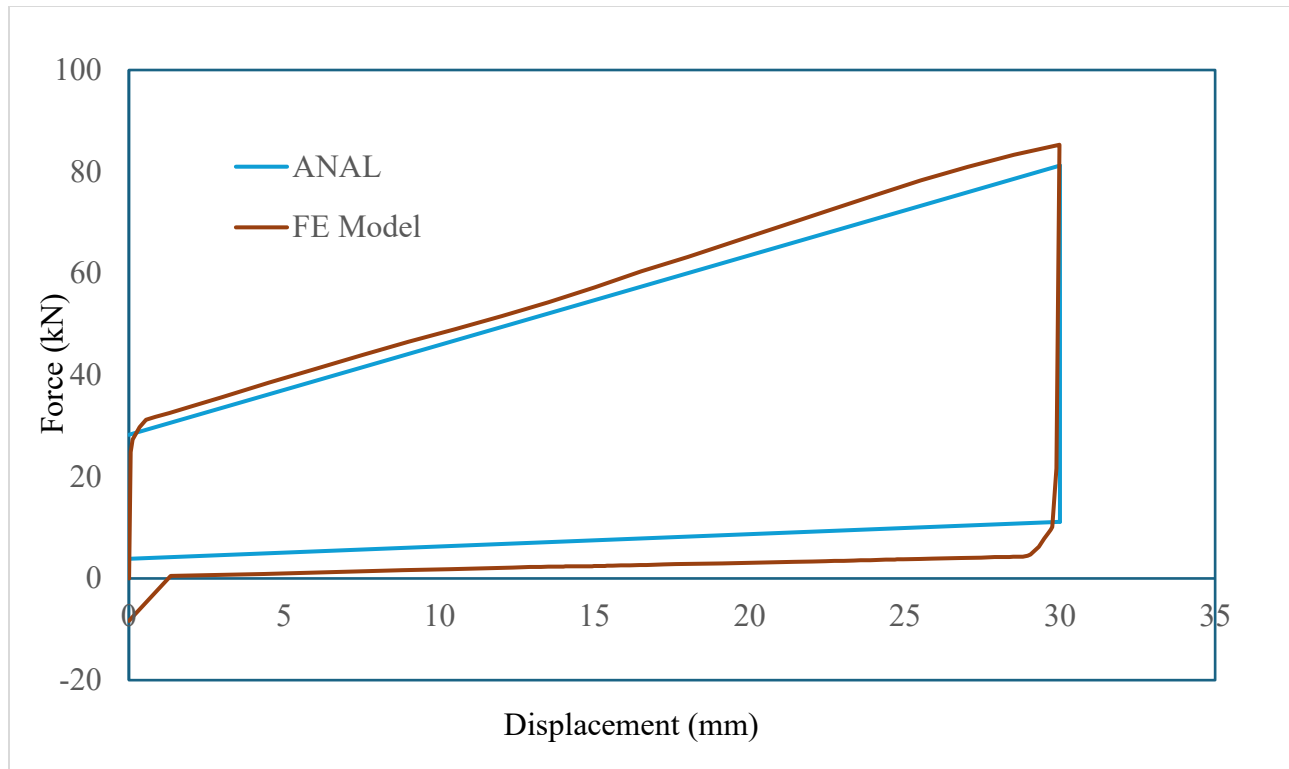


Fig3-7 Hysteretic behavior for FE model compared to the analytical prediction.

	Analytical E.Q	FE model	ANAL/FE
F_{slip} (kN)	28	31	0.91
F_{ult} (kN)	81	85	0.96
$K1$ (kN/mm)	1.77	1.8	0.99
Damping	1350	1550	0.88

Table-3 the analytical equations compared with FE model

3. JOINT'S PARAMETERS EFFECTS.

For this section, some of the influencing parameters affecting the performance of RSFJs are investigated. By fixing the external configuration of the Resilient Slip-Friction Joint (RSFJ), i.e., maintaining a constant bolt count(n_b) and, angle of the grooved plates (θ) and, the plates' dimensions, the parameters available for parametric investigation are confined to:

- (1) the stiffness of the restoring springs.
- (2) the pre-tension force applied to the bolts.
- (3) the friction coefficient between the sliding interfaces.

3.1 STIFFNESS OF THE RESTORING SPRINGS.

To assess the influence of the restoring springs' stiffness on the RSFJ response. The spring stiffness was varied from 6 to 16 kN/mm, while the target displacement was kept constant for all cases. The hysteresis curve was generated for each stiffness level. The force–displacement responses in Fig4-1& Fig4-2 demonstrate that, the slip force remains invariant across all levels. This behavior is attributed to the fact that F_{slip} is primarily governed by the frictional mechanism and bolt pre-tension, rather than by the presence or stiffness of the restoring springs.

Conversely, the ultimate force F_{ult} exhibits a clear dependency on the spring stiffness, specifically, increasing the spring stiffness led to a higher F_{ult} . consequently, an improved load- carrying capacity of the joint.

The observed effects are not limited to the increase in the ultimate force (F_{ult}) The force–displacement curves further indicate a clear increase in the loading stiffness of the joint with increasing restoring spring stiffness. As the spring stiffness increases the loading branches of the hysteresis loops become steeper, reflecting a higher resistance to deformation. Consequently, the combined increase in both (F_{ult}) and the loading stiffness leads to an expansion of the enclosed hysteresis loop area. This enlarged hysteretic area corresponds to a greater energy dissipation capacity, indicating that the joint is capable of absorbing higher energy as the restoring spring stiffness increases.

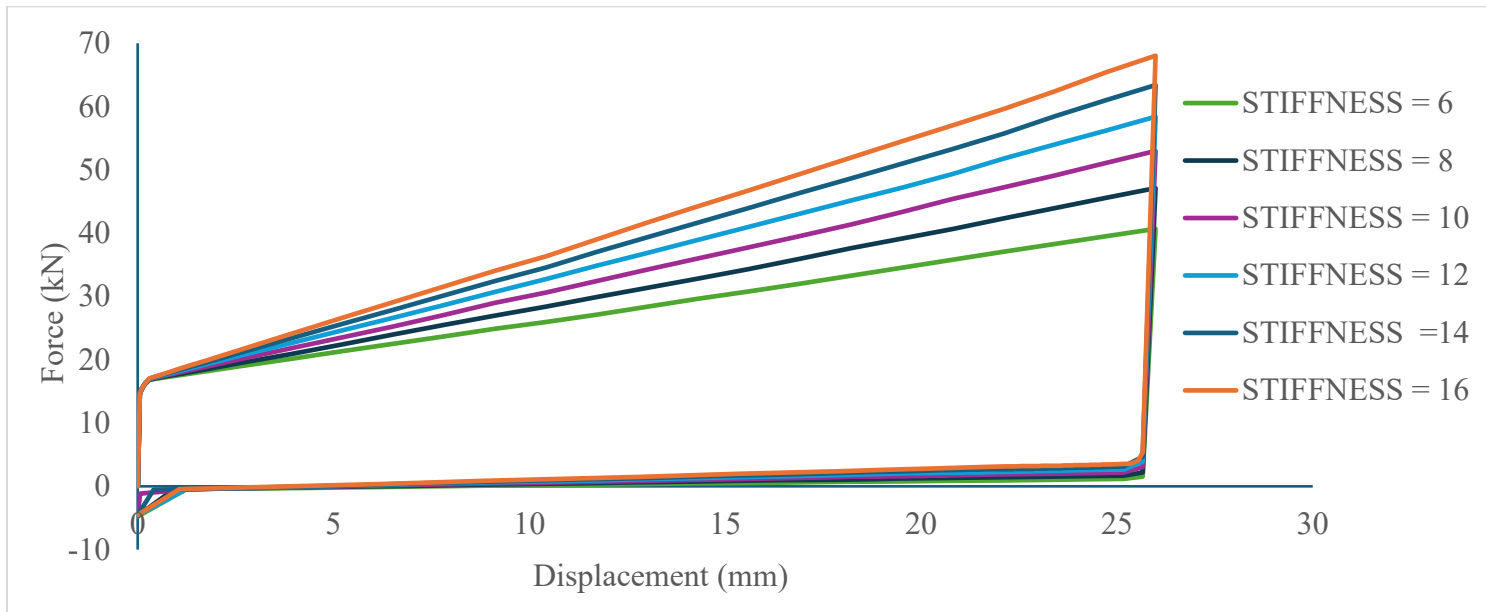


Fig4-1 Hysteretic behavior for variable spring stiffness value

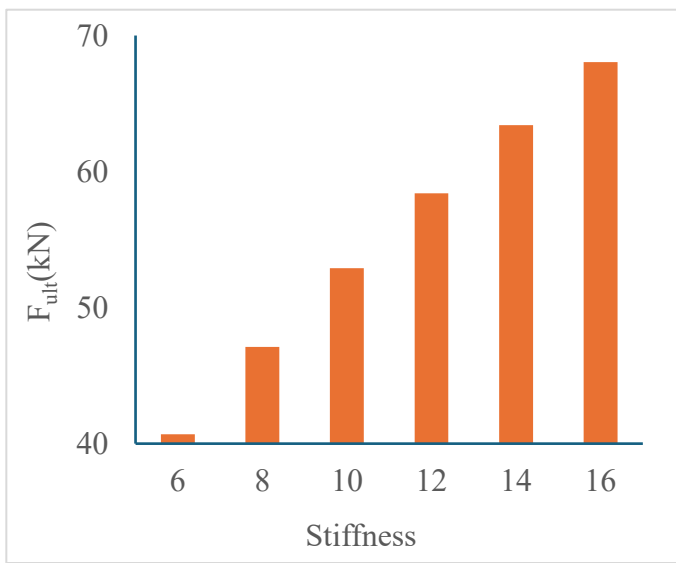


Fig4-2-A effect of changing stiffness value on F_{ult}

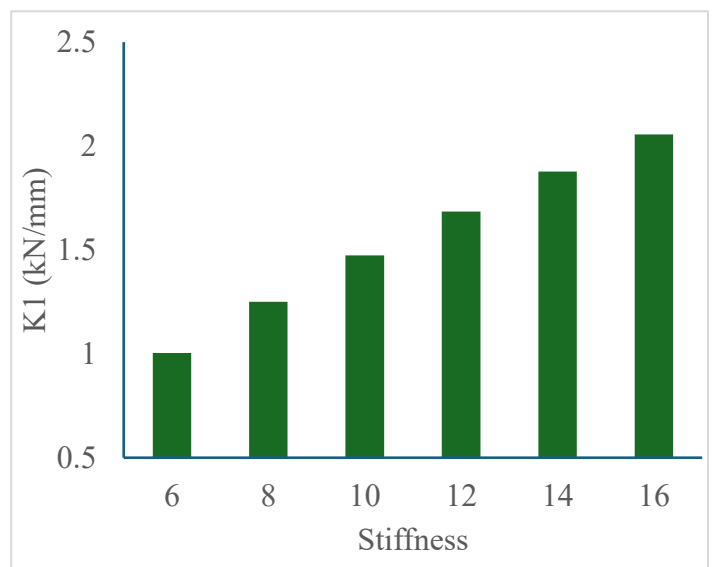


Fig4-2-B effect of changing stiffness value on K_1

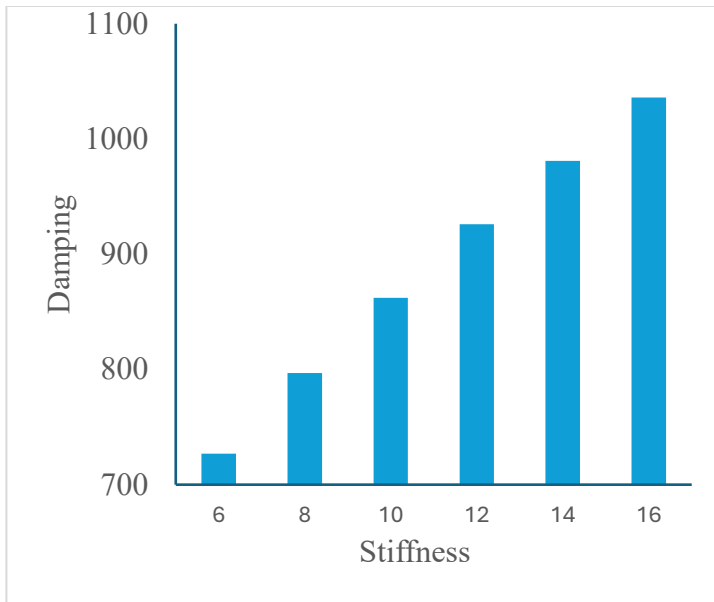


Fig4-2-C effect of changing stiffness value on damping

3.2 PRE-TENSION FORCE.

The effect of the pre-tension force applied to each bolt in the connection was investigated by developing several finite element models with different pre-tension force levels ranging from 15 kN to 42 kN, and the resulting force–displacement responses, illustrated in Fig4-3 & Fig4-4, clearly indicate a significant increase in the sliding force with increasing bolt pre-tension. This enhancement in sliding resistance provides the connection with higher initial rigidity. Moreover, the results reveal that the ultimate force (F_{ult}) increases with higher levels of bolt pre-tension.

The results indicate that, despite increasing the bolt pretension force, the slope of the loading branch remained parallel in the studied cases, indicating that, loading stiffness was not influenced by the variation in pretension force. However, a notable increase in the enclosed area of the hysteresis loops is observed with increasing bolt pre-tension. This enlarged hysteretic energy dissipation capacity reflects an enhancement in the damping behavior of the connection. Consequently, increasing the pre-tension force substantially improves the overall efficiency and seismic performance of the join

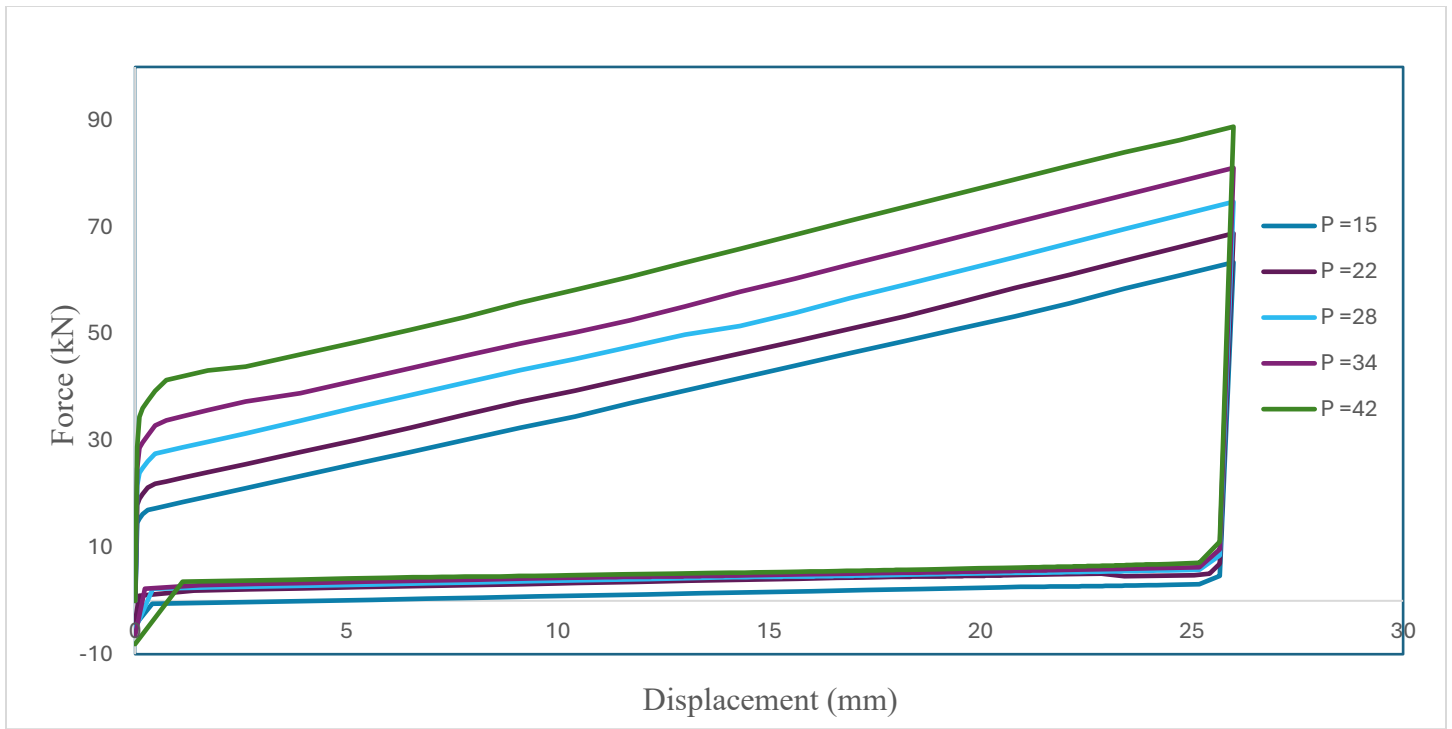


Fig4-3 Hysteretic behavior for variable pre-tension force value

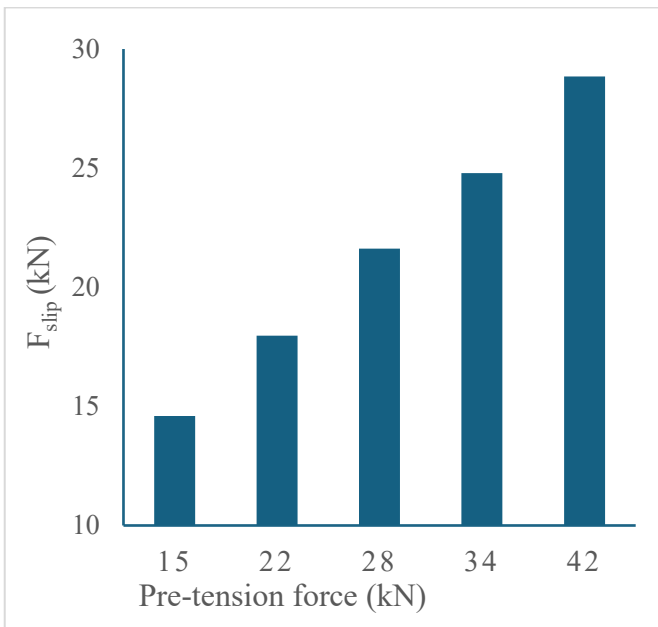


Fig4-4-A effect of changing Pre-tension force on F_{slip}

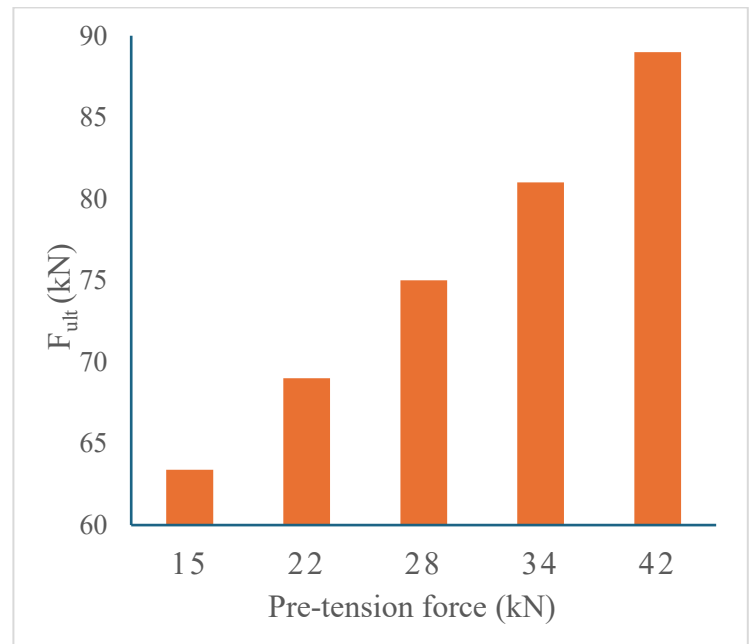


Fig4-4-B effect of changing Pre-tension force on F_{ult}

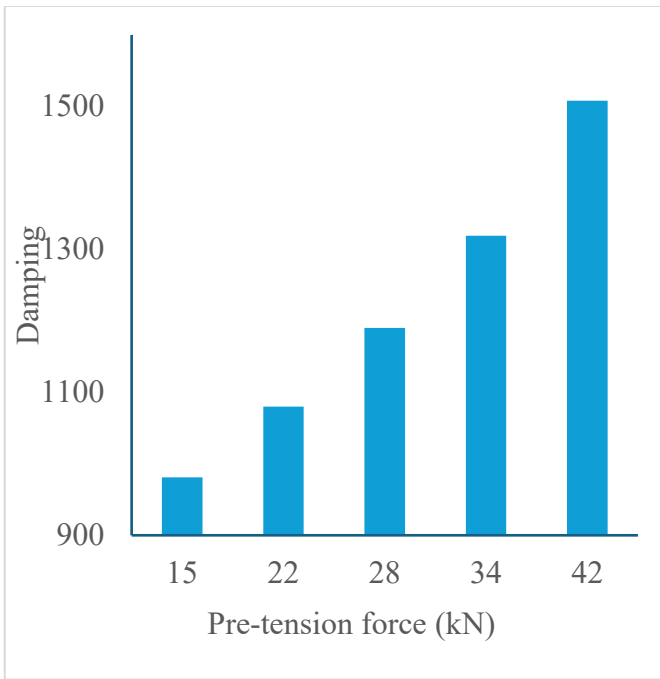


Fig4-4-C effect of changing Pre-tension force on damping

3.3 FRICTION BETWEEN MOVABLE PLATES.

First, it should be noted that for achieving a self-centering behavior in the joint, it is necessary to satisfy $\mu_s < \tan\theta$. [9]. To investigate the effect of friction, a detailed evaluation of the force–displacement hysteresis curves was carried out for friction coefficients ranging from 0.14 to 0.19. The results in Fig4-5 & Fig4-6 show that variations in friction exert limited influence on the slip force (F_{slip}), within the present examined range.

However, a noticeable increase in the ultimate force (F_{ult}) is observed with increasing friction coefficient for the same imposed displacement level. This trend indicates that higher frictional resistance effectively enhances the maximum load-carrying capacity of the joint, thereby improving its strength characteristics. This enhancement is also reflected in the loading branch of the hysteresis curves, where an increase in loading stiffness is evident with higher friction values, demonstrating a stiffer and more resistant response of the joint during the loading phase.

Moreover, the influence of friction is not confined to the loading phase., The increase in loading leads to a noticeable expansion of the flag-shaped hysteresis loop. This widening of the hysteretic envelope is directly associated with an enhancement in the energy dissipation capacity of the RSFJ, thereby signifying an improved ability of the joint to absorb and dissipate seismic input energy while retaining its characteristic self-centering, flag-shaped performance.

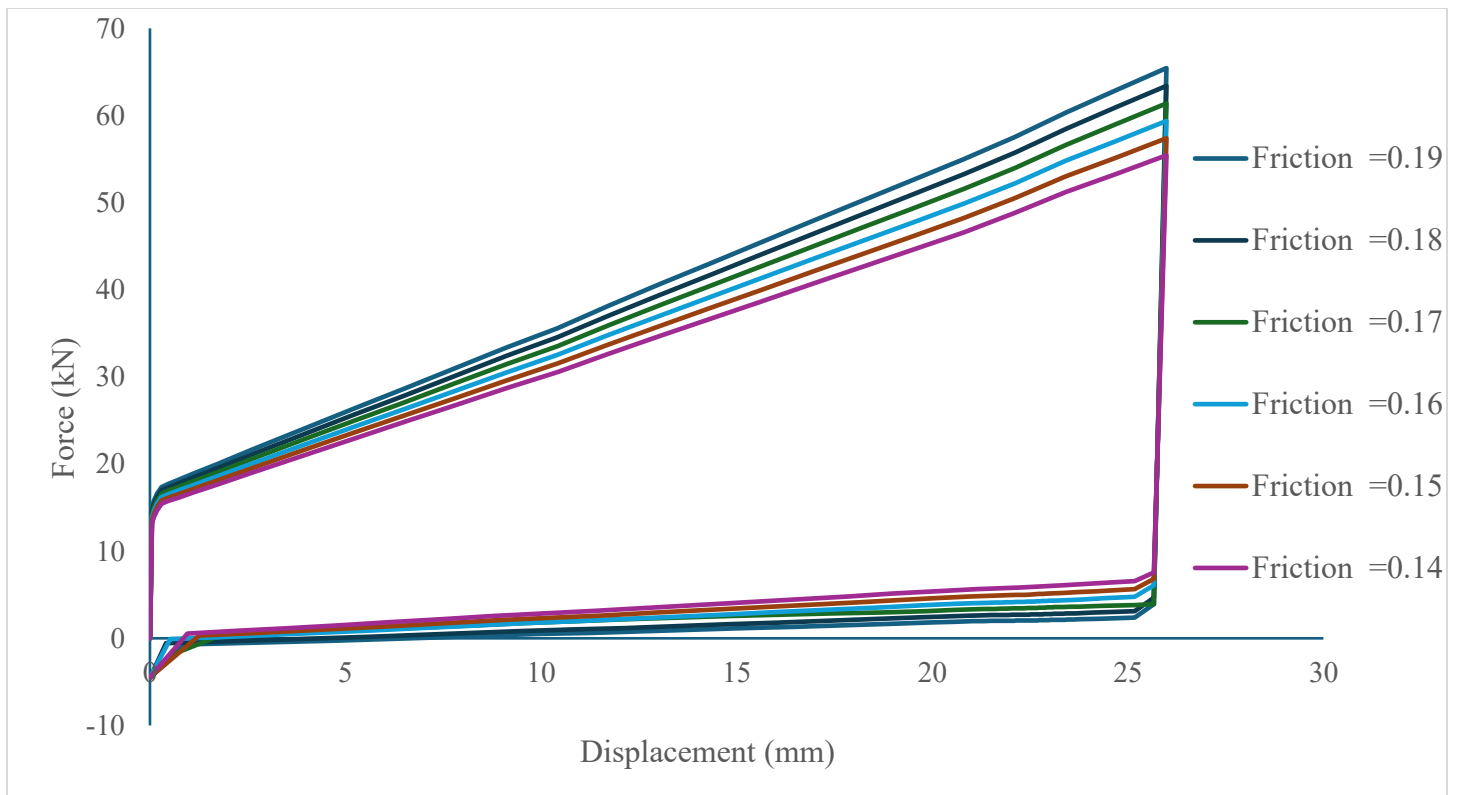


Fig4-5 Hysteretic behavior for variable friction value.

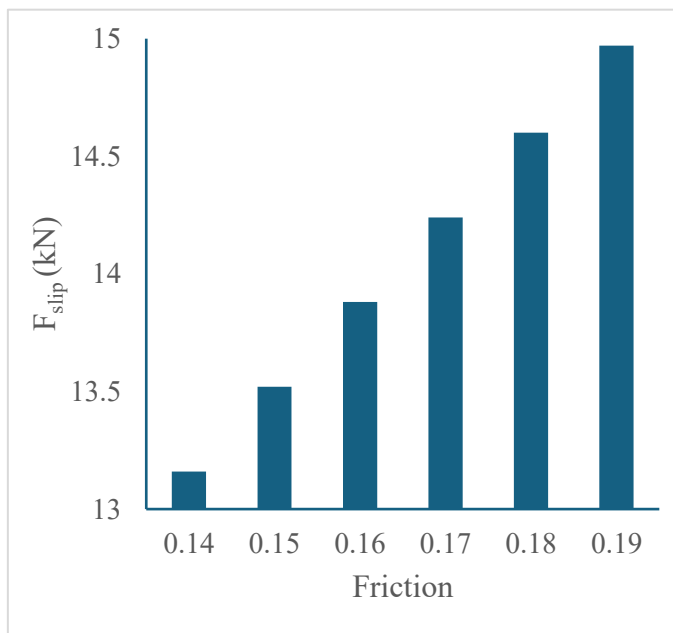


Fig4-6-A effect of changing Friction on F_{slip}

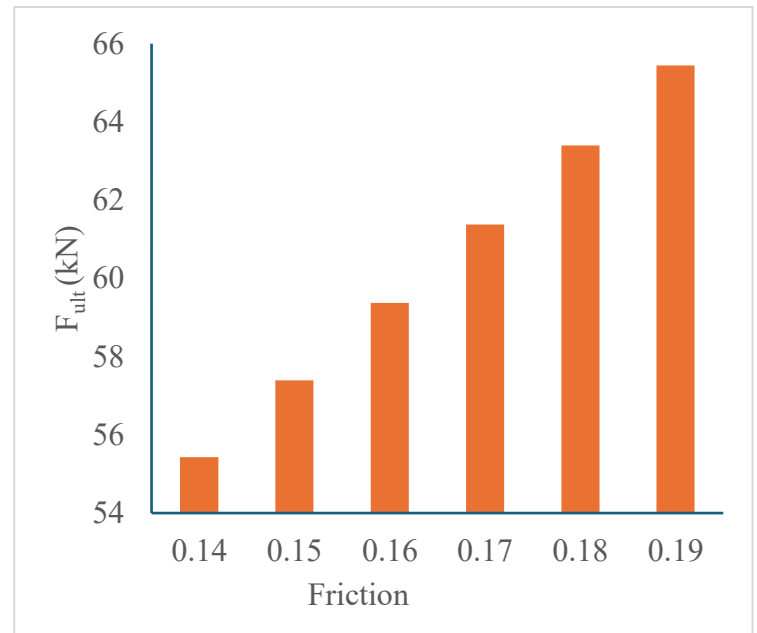


Fig4-6-B effect of changing Friction on F_{ult}

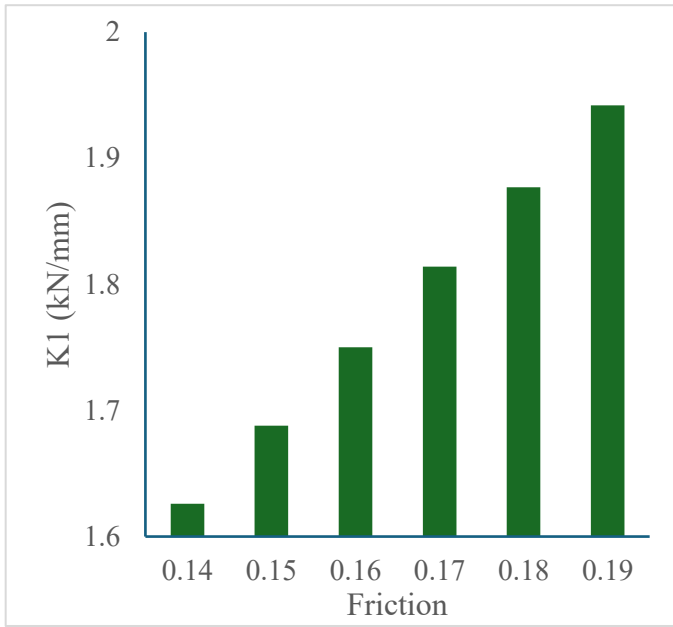


Fig4-6-C effect of changing Friction on K1

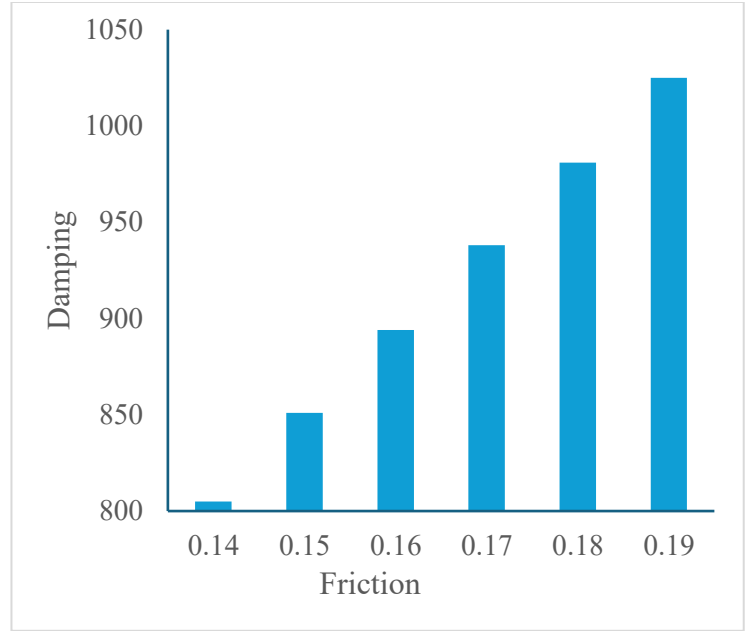


Fig4-6-D effect of changing Friction on damping

3.4 DISCUSSION OF RESULTS.

Upon completing the parametric investigation, a reference joint case was fixed and employed as a baseline configuration against which, all other cases were compared. This procedure ensured a clear and consistent identification of the individual effect of each parameter on the overall joint response. Table4-4 summarizes the results of all investigated cases, with the previous results normalized to the reference joint to facilitate a clear comparison of the relative effects of the studied parameters.

It should be noted that, the properties of the reference joint are: stiffness of springs =14 kN/mm, pre-tension of bolts =15 kN and, friction coefficient =0.18, keeping the joint external configuration as explained before.

Variable parameter		F _{slip} (kN)	F _{ult} (kN)	K1 (kN/mm)	Damping
Stiffness of spring (kN/mm)	6	100%	64%	53%	74%
	8	100%	74%	67%	81%
	10	100%	83%	79%	88%
	14	100%	100%	100%	100%
	16	100%	107%	110%	106%
Pre-tension of bolts (kN)	15	100%	100%	100%	100%
	28	178%	118%	100%	121%
	34	221%	128%	100%	134%
	42	274%	140%	100%	154%
Friction coefficient	0.14	90%	87%	87%	82%
	0.15	93%	91%	90%	87%
	0.16	95%	94%	93%	91%
	0.18	100%	100%	100%	100%
	0.19	103%	103%	103%	104%

Table-4 values normalized to the reference joint

As indicated in Table-4, F_{slip} value remained unaffected by the spring stiffness, since the spring does not engage in the mechanism until the slip force is exceeded. Additionally, changes in the friction coefficient resulted in only marginal variations in F_{slip} , ranging from 90% to 103% relative to the reference case, indicating a relatively minor influence. In contrast, the bolt pretension force exhibited a significant impact resulting in an increase in F_{slip} value to 274% compared to the reference case. This observation demonstrates that increasing the pre-tension force delays the activation of the Resilient Slip Friction Joint (RSFJ) mechanism.

Regarding F_{ult} , the tabulated results clearly demonstrate that increasing the spring stiffness led to an increase in F_{ult} , ranging from 64% to 107% compared to the reference joint. Similarly, increasing the pre-tension force enhanced F_{ult} by approximately 40%. Furthermore, modifying the friction coefficient led to an increase in F_{ult} of about 30% compared to the reference joint which is a considerable increase. It is worth noting that although the variation in the friction coefficient itself was relatively small, there was an appreciable change in F_{ult} , highlighting the sensitivity of the joint's ultimate strength to frictional properties. Collectively increasing each of the present parameters leads to a higher ultimate force for the joint, which is an essential factor in design considerations.

The results indicated in the table show that, the joint stiffness (K_1) during loading increases with the spring stiffness, ranging from 53% to 110% compared to the reference joint, which is considered a significant change. (K_1) also increases with higher friction coefficients, reaching a 30% increase relative to the reference joint. Meanwhile, variations in the pre-tension force do not affect the value of (K_1).

Since energy dissipation is a key function of the joint, damping represents an essential evaluation criterion. The table shows that increasing the spring stiffness caused damping to vary between 74% and 106%. Likewise, an increase in pre-tension force enhanced damping by approximately 54% relative to the reference joint. In addition, higher friction coefficients led to damping increases ranging from 82% to 104% compared to the reference joint. Overall, the results indicate that higher values of the studied parameters led to an improvement in the damping performance of the joint.

3.5 RESIDUAL DISPLACEMENT

Although the fundamental concept of the joint is based on providing self-centering capability, residual displacements were observed in both the present finite element simulations and the previous experimental tests. These residual displacements may be attributed to, minor contact imperfections in the experimental tests. The residual displacements in the FE simulations are referred to localized micro-slip effects, which involve small regions of relative sliding between contact surfaces while other regions remain stuck, used in the contact simulation performed in ABAQUS. Nevertheless, these residual displacements were very small (did not exceed 2 mm), indicating that the overall self-centering performance of the joint is effectively maintained.

4. CONCLUSION.

- 1- The developed finite element model for Resilient slip Friction Joint (RSFJ) has been successfully validated through comprehensive comparisons with both experimental results and analytical formulations.
- 2- This developed model can be considered a robust and efficient tool for simulating the mechanical behavior of RSFJs and can be confidently employed for parametric studies, performance evaluation, and further development of self-centering structural systems under cyclic loading.
- 3- The present finite element model was employed to conduct a comprehensive parametric study of the connection, focusing on the effects of spring stiffness, bolt pre-tension force, and friction coefficient. Analysis results were normalized to a reference joint to evaluate the effect of each parameter.

- 4- F_{slip} is a measure for the force at which the mechanism of the joint starts to work and, it is highly affected by the bolt pre-tension force.
- 5- F_{ult} which represents the maximum load capacity of the joint corresponding to a maximum specified displacement, can be improved by increasing any of the studied parameters. however, the spring stiffness exhibited a more significant influence than other variables.
- 6- The joint stiffness during loading K_1 , which contributes to the global stiffness of structure under seismic load, is significantly governed by the spring stiffness and friction coefficient of the joint.
- 7- RSFJ is inherently an energy dissipative system, so the damping capacity is treated as a key performance indicator. Our parametric study showed that, damping can be improved by increasing any of the studied parameters, especially the bolt pretension force.

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[13]	(ABAQUS/CAE 2020)