

## **A New Self-Centering Tension-Only Brace for Seismic Proofing of New and Existing Structures**

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### **Abstract**

The objective of this research is to introduce a self-centering tension-only brace employing Resilient Slip Friction Joint (RSFJ) applicable for seismic proofing of new and existing structures. This brace features self-centering, non-pinching behavior, energy dissipation and simplicity of design and implementation. Non-linear time-history analyses (NLTHAs) have been performed on a simple 2D steel braced frame designed with a displacement ductility of unity. First, a conventional tension-only brace has been employed and then RSFJs were added to the same frame at the end of the previous braces. Thanks to the superior performance of the RSFJ, the seismic base shear of the frame decreased by a factor of 3. Moreover, a full-scale 5 m high by 3.1 m long simple 2D steel frame has been designed and erected with the RSFJs to undergo cyclic, dynamic and time-history regimes of loading to illustrate the performance of the brace experimentally. Following the numerical modeling and test programs conducted so far, this brace can entice the practitioners into utilizing it in damage-avoidant construction and seismic upgrading up to design level earthquake.

Keywords: RSFJ, tension-only, self-centering, damage-avoidant, retrofitting

## 1 Introduction

This paper proposes a new self-centering tension-only brace equipped with the Resilient Slip Friction Joints (RSFJs). The new tension-only brace can be adopted in new buildings or in existing buildings as a retrofitting technique to provide the self-centering capability, energy dissipation and enhanced ductility for structures while it requires no post-event maintenance up to design level earthquake (Ultimate Limit State, ULS) owing to the flag-shape hysteretic response of the RSFJ. As such, structures equipped with this new seismic technology can be deemed fully operational even after severe earthquakes.

Tension-only braces have extensively been used in low- to mid-rise industrial and commercial steel buildings worldwide since they are simple to design and cost-efficient to be constructed [1]. However, structures including the conventional tension-only braces (that are designed according to the current design codes) may suffer from a severe pinching behaviour when subjected to intense events since they are designed to yield under tension and to buckle under compression loadings. This would lead to a long downtime and financial loss as repairs would be required following an event.

Steel bracing systems have been used for seismic retrofitting of existing structures including reinforced concrete (RC) frames [2–7] and steel frames in order to enhance the lateral strength, stiffness and ductility of the structure. F.J. Molina et al. [5] performed seismic tests on 3-story reinforced concrete and steel frames retrofitted with pressurized fluid-viscous spring dampers. These dampers were installed through K-bracing between different floors. Results showed the capability of such devices in a structure in decreasing the seismic forces. L Di Sarno and A.S. Elnashai [8] assessed the seismic performance of a 9-story steel perimeter moment resisting frame that was intentionally designed to have insufficient lateral stiffness to satisfy the code drift limitations in high seismic hazard zones. The three different retrofitting techniques investigated by the authors were Special Concentrically Braces (SCBFs), Buckling-Restrained Braces (BRBFs) and Mega Braces (MBFs). Results of their research demonstrated that the MBFs had the best performance in mitigating lateral drift amongst the three. D Li Sarno et al. [9] probed the design issues, advantages and disadvantages of the innovative strategies for the retrofitting of existing structures. They included base isolation, friction, viscous, viscoelastic and shape memory alloy (SMA) dampers in their study. The viability and cost-effectiveness of these strategies were assessed based on the multiple limit states of the performance-based design. Finally, they concluded that selection of a proper strategy for seismic upgrading of a structure is governed by the following factors:

- Efficiency;
- Compactness;
- Weight;
- Capital and operating costs;
- Maintenance requirements;
- Safety;

This paper introduces the RSFJ tension-only bracing system as an efficient and cost-effective retrofitting technique possessing the abovementioned characteristics. This technique can be used for RC frames, steel MRF and specifically steel braced frames.

## 2 Resilient Slip Friction Joint (RSFJ)

The RSFJ is a joint that can provide self-centering capability alongside with energy dissipation all in one compact device. It has been developed by Zarnani and Quenneville [10] in 2016 and then was introduced to the NZ construction industry. Previous technology providing a self-

centering behaviour include pre-stressed tendons and SMAs with supplemental dampers such as friction sliders or yielding parts. In these systems, the need to have an additional source of damping as well as the practical difficulties of using the pre-stressed tendons, (such as losing the pre-stressing force over the time [11]) was a motivation to have a joint that can offer these two characteristics in one package. The components of the RSFJ, as shown in Figure 1 (a) are grooved slotted middle plates, grooved cap plates with simple holes, high-strength bolts/rods and nuts and disc springs. The assembly of the joint is shown in Figure 1 (b). The boundary conditions of the joint can be fixed or pinned based on the design demand.

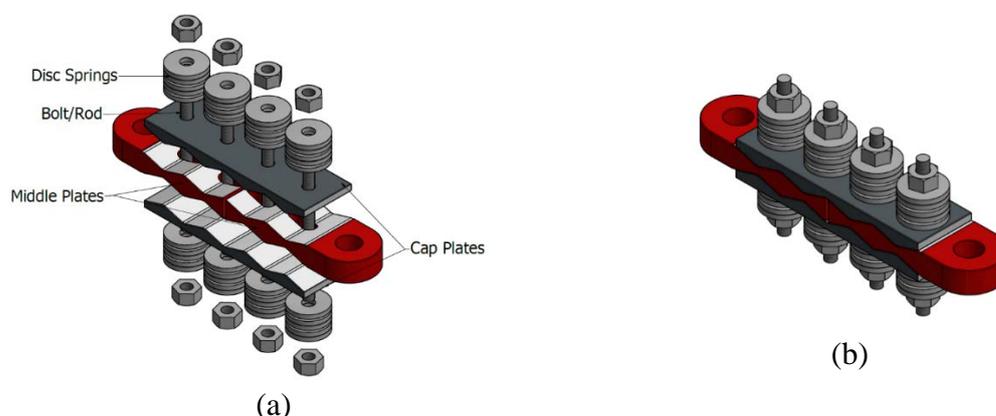


Figure 1: (a) components of the RSFJ (b) RSFJ assembly

The clamping bolts/rods and disc springs are initially pre-stressed to a force based on the design demand. When the joint is loaded, the initial static frictional resistance between the clamped grooved surfaces is overcome and the device starts opening up; the corresponding external force on the joint is called the slipping force,  $F_{slip}$ . Then as the loading increases and the joint keeps opening up, the sliding friction mechanism dissipates the energy until the disc springs are fully flattened and are locked; this is the ultimate state of the device and the corresponding external force on the joint is called the ultimate force,  $F_{ult}$ . As the external load is removed (the unloading begins), the pre-stressed bolts/discs bring back the joint to its initial position; the corresponding external force as the joint starts slipping back is called the restoring force,  $F_{rest}$ . The minimum force immediately before the joint returns to its initial position is called the residual force,  $F_{resid}$  [12]. As such, during each cycle, both energy dissipation and self-centering are provided by the joint. In Figure 2, the hysteretic cycles of the joint performance, the so called flag-shape hysteresis, as well as the force characteristics of the joint and the ultimate deformation,  $\Delta_{ult}$ , are illustrated. The area enclosed by the curve represents the amount of energy dissipated.

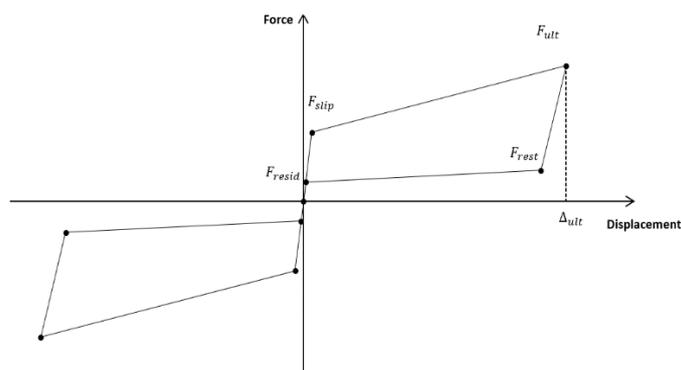


Figure 2: Flag-shape hysteresis of the RSFJ

Based on the free body diagram shown in Figure 3, the following equations can be derived for the joint [11]:

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

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

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

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

Where  $n_b$  is the number of bolts on each splice of the joint, e.g.  $n_b = 2$  in Figure 1,  $F_{b,pr}$  is the pre-stressing force of each bolt,  $\theta$  is the angle of the grooves,  $\mu_s$  and  $\mu_k$  are the static and kinetic coefficient of friction between the sliding surfaces which based on the grease used between the surfaces, are respectively 0.19 and 0.16.  $F_{b,ult}$  is also the bolt force at the ultimate state of the joint which is equal to the flat load of the disc springs, if they are used in series. The  $\Delta_{ult}$  of the joint is derived from equation (5).

$$\Delta_{ult} = 2 \frac{\Delta_s}{\tan \theta} \quad (5)$$

In which  $\Delta_s$  is the maximum deflection of the stack of the discs on each side of a single bolt. The performance of the joint up to the ultimate force is a flag-shape. This ultimate point can be designed to match ultimate limit state (ULS) or the maximum considered event (MCE) or even larger events. This is determined based on the level of performance expected from the structure and the joint itself. In addition to this, the joint can have a ductile behaviour beyond the ultimate force which is called the ‘secondary fuse mechanism’. The ‘secondary fuse’ mechanism is to ensure that events larger than what are expected are still controlled by the device. This mechanism is reached by yielding of the pre-stressing bolts and they can be replaced after a larger-than-expected event. The mechanism is designed in a way to maintain the self-centering of the joint after it is activated. The reader is referred to [13], [14] for more information about the secondary fuse including the experimental test results and design equations. In Figure 4, the flag-shape behaviour of the joint with added secondary fuse mechanism is displayed.

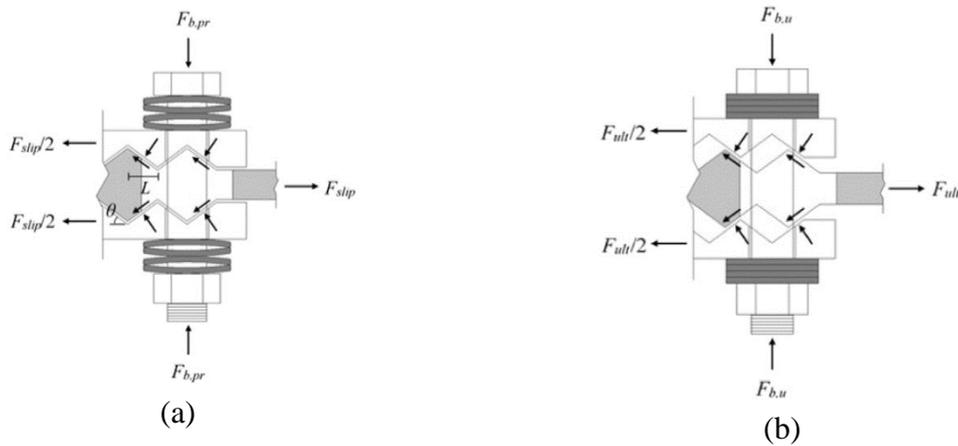


Figure 3: Free body diagram of the RSFJ at (a) slip state (b) ultimate state [11]

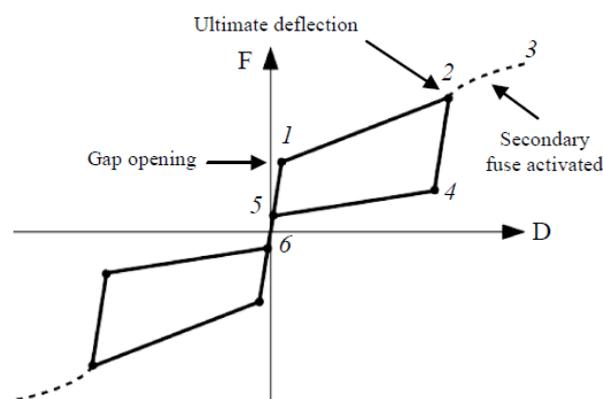


Figure 4: The flag-shape response of the RSFJ including the effect of the collapse-prevention secondary-fuse mechanism [13]

The RSFJ is designed to have a repeatable behavior in tension or compression (or both) within the target design demand. As mentioned, after that, the secondary fuse is activated which is the collapse-prevention over-strength mechanism for forces larger than the design force. Figure 5 shows the first full-scale RSFJ that was subjected to cyclic tests. It was demonstrated that the performance of the RSFJ is stable and responds as per the theoretically predicted behaviour. The joint was designed to work in tension and compression but the demonstration test was only in tension.

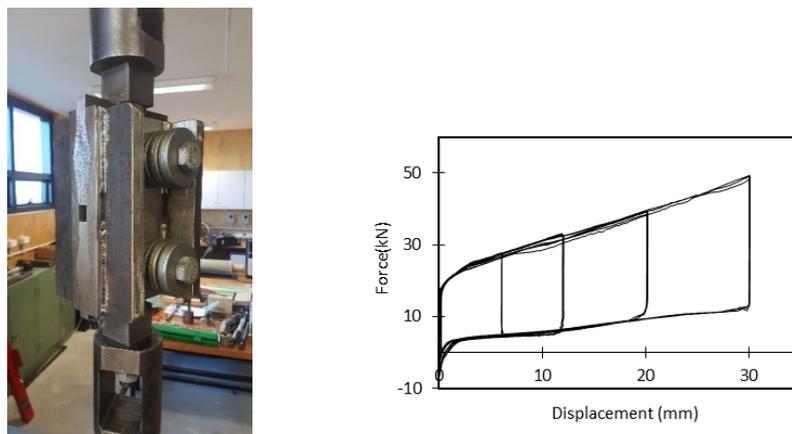


Figure 5: Joint component testing of the RSFJ [11]

### 3 RSFJ Tension-Only Brace

The RSFJ can offer a flag-shape behaviour in tension and in compression. Where a compression displacement is required, an initial gap between the two middle plates is included. In that case, the stability analysis of the joint is of importance to prevent the global buckling [14]. In the RSFJ tension-only brace, a rod, a plate or a Reidbar can be used for the brace body and based on the force demand required, the number of rods/plates/Reidbars can be adjusted. Also, based on the drift requirement, the RSFJs can be used on only one end of the rods/plates/Reidbars or on the two ends. As the braced frame is loaded, one of the diagonal braces elongates while the other one shortens. The deformation in tension is provided initially by the elastic behaviour of the system and then is provided by the RSFJ after slip. On the

compression member, due to the details displayed in Figure 6 (a), as the rods shorten, they will be released and will extend over the joint lateral surfaces. Therefore, there will be no compression force on the rods and RSFJs. In the opposite direction of loading, this procedure is reversed so in a full cycle, no member is yielding or buckling and there will be no pinching or slackness in the system.

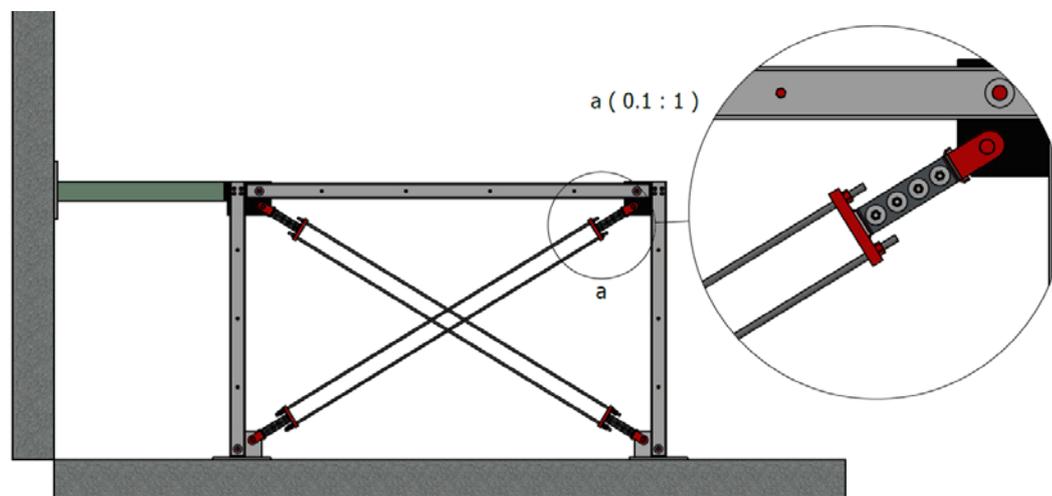


Figure 6: Designed test set-up: (a) details of the tension-only connection

#### 4 Numerical Modelling

In order to demonstrate the efficiency of the proposed tension-only brace in mitigating the seismic base shear of the conventional braced frames, a one-bay one-story 2D steel braced frame including tension-only braces with span length of 10 meters and height of 6 meters, typical to the industrial and commercial steel buildings, was modelled using the SAP2000 software [15]. Firstly, this frame with a design life of 50 years and importance level of 3 was designed based on the NZS1170.5 [16] and NZS3404 [17]. The design parameters as well as the uniform gravity loads applied to the beam are tabulated in Table 1. In this table, a structural ductility factor of  $\mu = 1.0$  was adopted to compare a ductile design using the RSFJs with an elastic design which usually is the case for tension-only bracing systems.

Table 1: Design parameters and loads of the investigated frame

Parameter	Definition	value
$\mu$	Structural ductility	1
Z	Hazard factor	0.4
R	Return period factor	1.3
D	Near fault distance (km)	20
$S_p$	Performance factor	0.7
G	Permanent load (kN/m)	13
Q	Imposed load (kN/m)	15

The designed brace body is a single M24 Reidbar with a yield strength of 500 MPa and the corresponding base shear is 167 KN based on the Equivalent Static Method (ESM). Then the RSFJs will be added to the braces bodies at the end to enhance the performance of the frame. One can use the Damper-Friction Spring link provided in ETABS and SAP2000 and specify the characteristics of the flag-shape of the RSFJ, i.e. stiffness and displacement of different

portions of the flag-shape behavior, to investigate their effects on the base shear reduction. The reader is referred to the CSI Analysis Reference Manual [18] and also [11] for more details on the joint numerical modeling. At this stage, based on the static pushover analysis performed, the joints characteristics were tuned to achieve a 2.5% drift under the ultimate limit state (ULS) base shear. These characteristics are summarized in Table 2. Moreover, the serviceability limit state (SLS) drift and the strength requirements were checked.

Table 2: Joint characteristics for numerical modeling

Property	$F_{slip}$ (kN)	$F_{ult}$ (kN)	$\Delta_{ult}$ (mm)
Value	27.5	42	60

In the next step, three earthquake records (Kobe, Fukushima 1995, Christchurch, Cathedral College 2011 and El Centro, Imperial Valley 1940) were scaled to the ULS according to NZS 1170.5 based on the parameters mentioned in Table 1 and then applied to the frame using the NLTHA method. The resulting hysteresis curve of the joint is plotted in Figure 7 and the maximum base shears resulted from the simulations (with and without RSFJs) are compared in Figure 8.

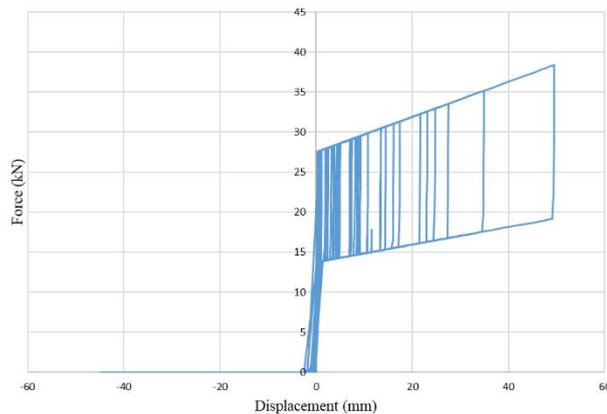


Figure 7: Hysteretic curve of the RSFJ response under El Centro 1940

This considerable base shear reduction is the result of the ductility and energy dissipation provided by the RSFJs while maintaining the self-centering capability.

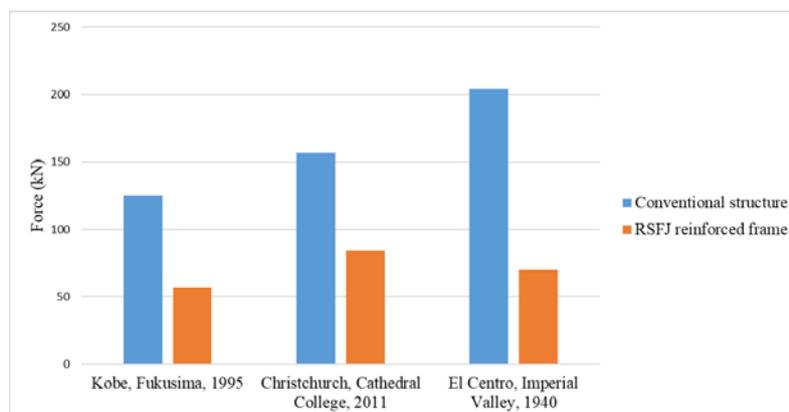


Figure 8: Comparison of maximum base shears under scaled earthquakes

## 5 Experimental Tests

In order to experimentally investigate the performance of the proposed tension-only brace, a full-scale 2D pinned tension-only braced frame with bay length of 5 m and height of 3.1 m was designed based on the NZS3404 [17] to obtain 2.5% and 5% drifts for horizontal forces of 160 and 215 kN respectively at the actuator, as per the frame shown in Figure 5. The resulting sections for beam, columns and braces are summarized in Table 3.

Table 3: Designed members sections and their specifications

Member	Beam	Columns	Braces
Section	Back to back PFC180, gap of 25 mm	Back to back PFC180, gap of 25 mm	2M24 rods
Steel grade	Mild steel	Mild steel	Grade 8.8

Joints were then designed to be located at both ends of the braces and the parameters and capacities are given in Table 4.

Table 4: Parameters and capacities of the designed joints for the experiment

Parameter	$n_b$	$n_d^*$	$\theta$ (deg)	$F_{slip}$ (kN)	$F_{ult}$ (kN)	$\Delta_{ult}$ (mm)
Value	2	11	17	125	250	60

\*:  $n_d$  is number of parallel discs per bolt per side

The testing is planned to be conducted in the University of Auckland Structures Test Laboratory and the frame will be tested under cyclic, dynamic and time-history records.

## 6 Conclusions

In this research, a new resilient tension-only brace is introduced where Resilient Slip Friction Joints (RSFJs) are attached to the tension-only diagonal braces to provide the required ductility and damping for the system. This bracing system can easily be installed to retrofit existing frames (to meet the damage avoidance design criteria) so that the structure will remain fully operational after the event as no post-event maintenance is required.

The performance of the RSFJ is experimentally verified on the component level and also full-scale experimental tests are planned to investigate the seismic performance of RSFJ tension-only braces. Furthermore, nonlinear dynamic time-history simulations are performed to show that the ductility and damping offered by the RSFJ can significantly reduce the base shear and increase the seismic performance index (score) of the building specially when compared to the existing diagonal tension-only bracing systems. In sum, the findings of this research shows the great potential of the proposed system for seismic proofing of new and existing buildings.

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