12TH CANADIAN CONFERENCE ON EARTHQUAKE ENGINEERING
JUNE 17-20, 2019
CHÂTEAU FRONTENAC
QUÉBEC, QC.
12ÈME CONFÉRENCE CANADIENNE DU GÉNIE PARASISMIQUE
17-20 JUIN 2019
CCEE 2019

A self-centering tension-only bracing system for seismic resistant structures using the Resilient Slip Friction Joint (RSFJ)

Hamed Bagheri[1], Ashkan Hashemi[2], S. M. M. Yousef-beik[3], Pouyan Zarnani[4], Pierre Quenneville[5]
[1]PhD Student, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand.
[2]Postdoctoral Research Fellow, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand.
[3]PhD Student, Department of Built Environment Engineering, Auckland University of Technology, Auckland, New Zealand.
[4]Lecturer, Department of Built Environment Engineering, Auckland University of Technology, Auckland, New Zealand.
[5]Professor of Timber Design, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand.

ABSTRACT

The objective of this paper is to introduce a self-centering tension-only brace using the Resilient Slip Friction Joint (RSFJ) for seismic proofing of new and existing structures. This brace exhibits self-centering, non-pinching and non-slack 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 to investigate the performance of this new system and compare it with the conventional elastic systems. On this frame, first, a conventional tension-only brace has been modelled and then RSFJs were added to the same frame at the end of the previous braces. Owing 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 with the RSFJs to undergo dynamic loading regime to illustrate the performance of the brace experimentally. Before this frame test, the designed joints were tested as components to verify their performance. Following the numerical modeling and completed testing programs, it can be concluded that this brace can entice the practitioners into utilizing it in damage-avoidance construction and seismic upgrading of existing structures; firstly because it can reduce the seismic base shear drastically and secondly the system is self-centered because of the flag-shape behavior of the joint and elastic behavior of other members under dynamic loading.

Keywords: seismic, cross-bracing, RSFJ, tension-only, self-centering, retrofitting

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 self-centering capability, energy dissipation and enhanced ductility for structures while it requires no post-event maintenance up to the 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 behavior when subjected to intense events considering the fact that 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.

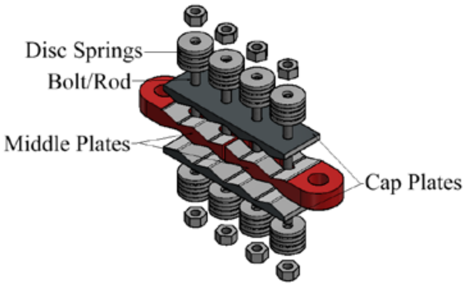
Steel bracing systems have been used for seismic retrofitting of existing structures including reinforced concrete (RC) frames [2–7] and steel frames in order to enhance the lateral strength, stiffness and ductility of the structure. F.J. Molina et al. [5] performed seismic tests on 3-story reinforced 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;

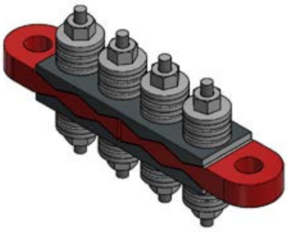
This paper introduces the RSFJ tension-only bracing system as an efficient and cost-effective retrofitting technique possessing the abovementioned characteristics. This technique can be used for RC frames, steel MRF and specifically steel braced frames.

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 invented by Zarnani and Quenneville [10] in 2015 and then was developed and introduced to the NZ construction industry. Previous technology providing a self-centering behavior 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.



(a)



(b)

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, Δ_{ult}, are illustrated. The area enclosed by the curve represents the amount of energy dissipated.

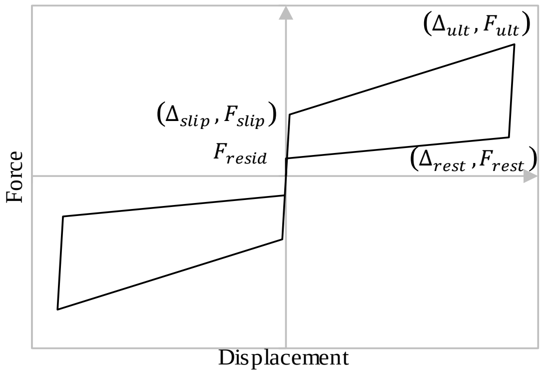


Figure 2. Flag-shape hysteresis of the RSFJ

Based on the free body diagram shown in Figure 3, the following equations can be derived for the joint [11, 13]:

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

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

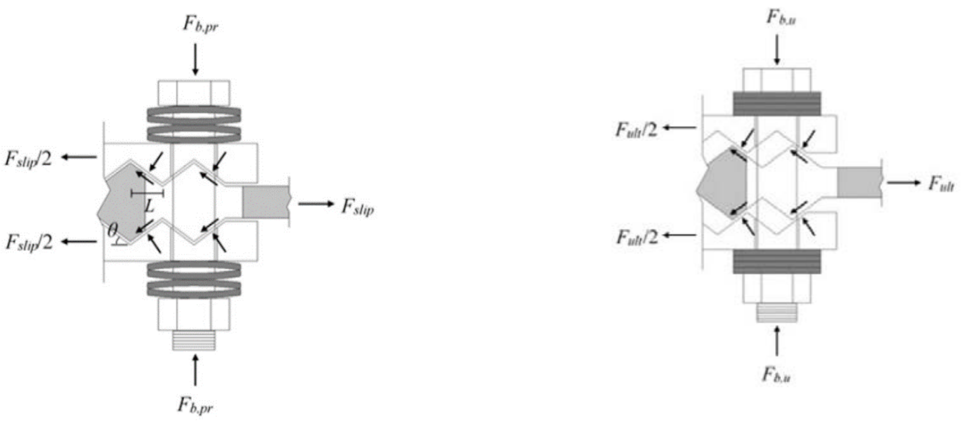
$$F_{rest} = 2n_b F_{b,ult} \left(\frac{\sin\theta - \mu_k \cos\theta}{\cos\theta + \mu_k \sin\theta}\right) \tag{3}$$

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

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, θ is the angle of the grooves, μ_k is the kinetic coefficient of friction between the sliding surfaces which based on the grease used between the surfaces, is 0.15-0.16. $F_{b,\,ult}$ 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 Δ_{ult} of the joint is derived from Eq. (5).

$$\Delta_{ult} = 2\frac{\Delta_s}{\tan\theta} \tag{5}$$

In which Δ_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 behavior 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 which 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 [14], [15] for more information about the secondary fuse including the experimental test results and design equations. In Figure 4, the flag-shape behavior of the joint with added secondary fuse mechanism is displayed.



(a) (b)

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

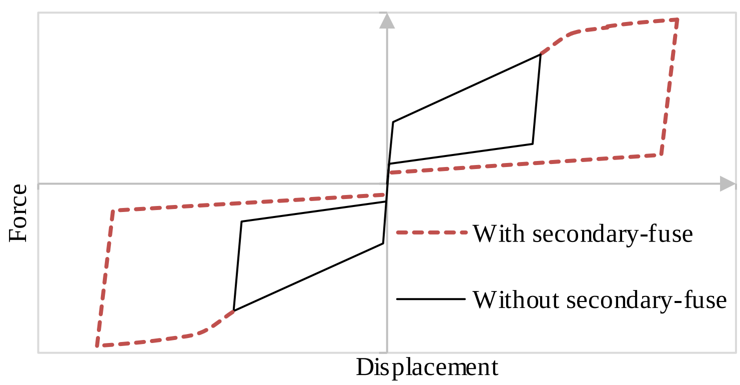


Figure 4. Flag-shape response of the RSFJ with and without the secondary-fuse mechanism

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 design force. Figure 5 shows the first full-scale RSFJ that was subjected to cyclic tensile tests. It was demonstrated that the performance of the RSFJ is stable and responds as per the theoretically predicted behavior.

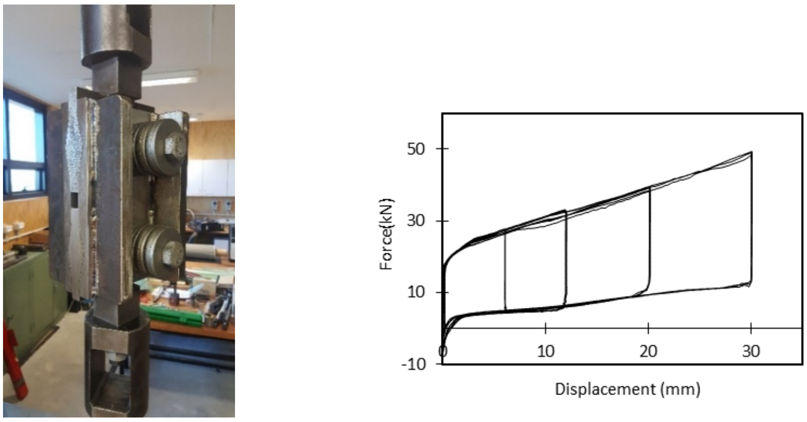


Figure 5. Joint component testing of the RSFJ [11]

RSFJ TENSION-ONLY BRACE

The RSFJ can offer a flag-shape behavior 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 [15]. 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 behavior of the system and then is provided by the RSFJ after slip. On the compression member, due to the details displayed in Figure 6, 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, a similar behavior is expected so in a full cycle, no member is yielding or buckling and there will be no pinching or slackness in the system.

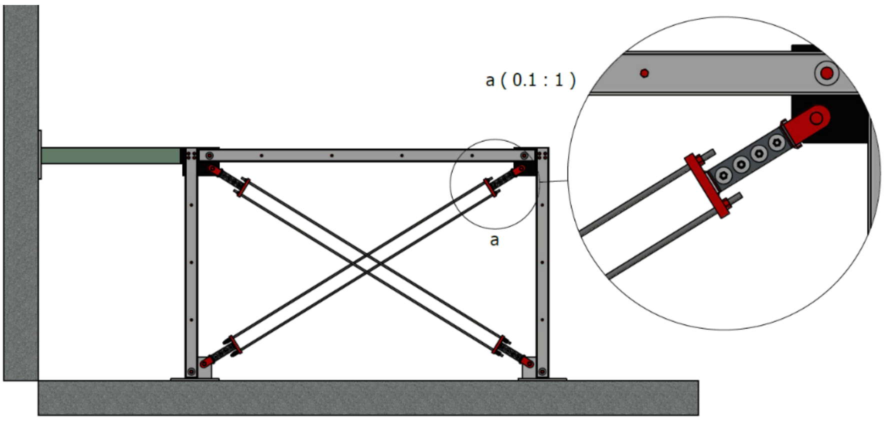


Figure 6. The designed test set-up

NUMERICAL MODELLING

In order to demonstrate the efficiency of the proposed tension-only brace in reducing 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 dimensions for the industrial and commercial steel buildings, was modelled using the SAP2000 software [16]. Firstly, this frame with a design life of 50 years and importance level of 3 was designed based on the NZS1170.5 [17] and NZS3404 [18]. 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 of 1.0 was adopted to compare a ductile design using the RSFJs with an elastic design.

Table 1: Design parameters and loads of the investigated frame

Parameter	**Definition**	**value**
μ	Structural ductility	1.0
Z	Hazard factor	0.4
R	Return period factor	1.3
D	Near fault distance (km)	20
S_p	Structural 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. The corresponding base shear is 167 kN based on the Equivalent Static Method (ESM). Then the RSFJs were added to the braces bodies at the end to retrofit the frame. One can use the Damper-Friction Spring link provided in 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 reference [19] 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)**	**Δ_{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. This considerable base shear reduction is the result of the ductility and energy dissipation provided by the RSFJs while maintaining the self-centering capability.

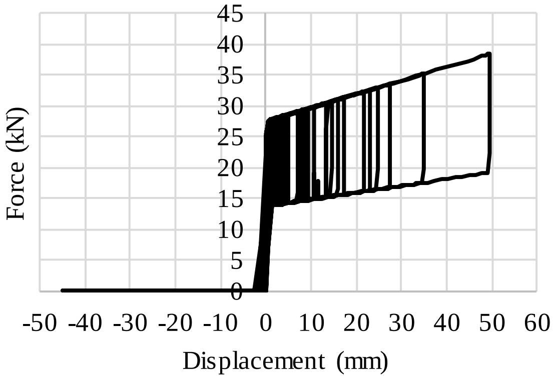


Figure 7. Hysteretic curve of the RSFJ response under El Centro 1940

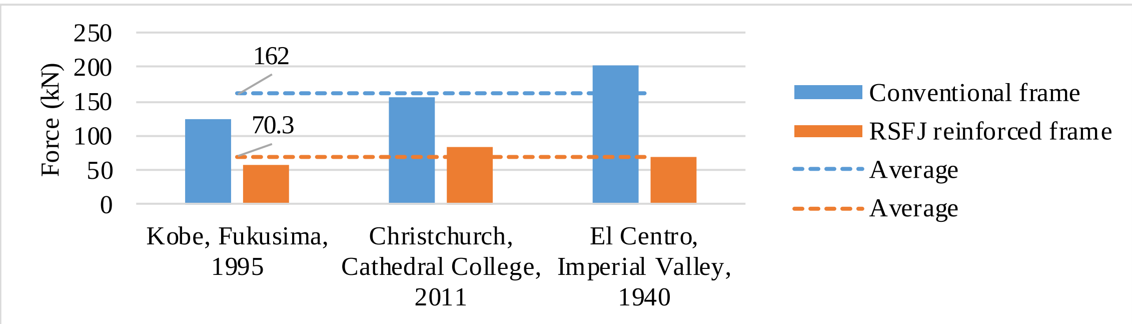


Figure 8. Comparison of maximum base shears under the scaled earthquakes and their average

EXPERIMENTAL TESTS

Frame and joints design

In order to experimentally investigate the performance of the proposed tension-only brace, a full-scale 2D tension-only braced frame with span length of 5 m and height of 3.1 m was designed based on the NZS3404 [18] to obtain up to 5% drift, as per the frame shown in Figure 6. The resulting sections for the beam, columns and braces are summarized in Table 3.

Table 3: Designed members sections and their specifications

Member	Beam	Columns	Braces
Section	Double PFC180 (back to back), gap of 25 mm	Double PFC180 (back to back), gap of 25 mm	2 M24 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	$\mathbf{n_b}$	$\mathbf{n_d^*}$	**θ (deg)**	$\mathbf{F_{slip}}$ **(kN)**	$\mathbf{F_{ult}}$ **(kN)**	$\mathbf{\Delta_{ult}}$ **(mm)**
Value	2	11	17	125	250	60

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

Joint component testing

Before installing the joints in the frame, each one of them was tested to verify the performance of the joint and obtain the displacement-force relationship. The force in the joint was measured by the internal load cell mounted on the actuator and the displacement between two middle plates was measured using a Linear Variable Differential Transformer (LVDT). Figure 9 shows the component testing set-up and one of the joints under maximum displacement.

(a) (b)

Figure 9. RSFJ component testing: (a) setup, (b) RSFJ at the maximum designed displacement (60 mm)

Figure 10 demonstrates the test result of the joints and compares it to the estimated response which as shown, the test result and the estimation are matching. The reason for slight non-linear jump at the top-right corner of the recorded flag-shape is the non-linear behavior of the disc springs as they are close to be fully flattened. Note that all four joints were tested and their responses were quite close.

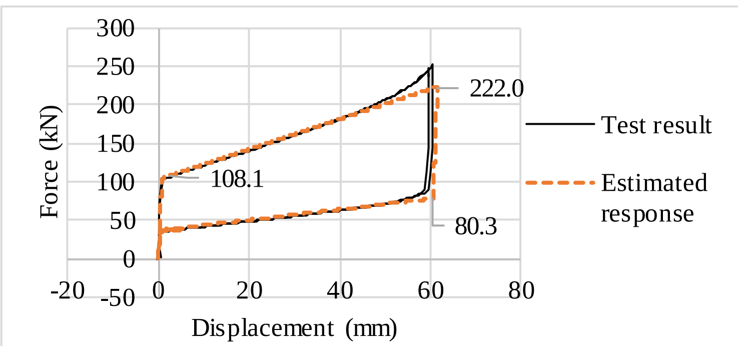


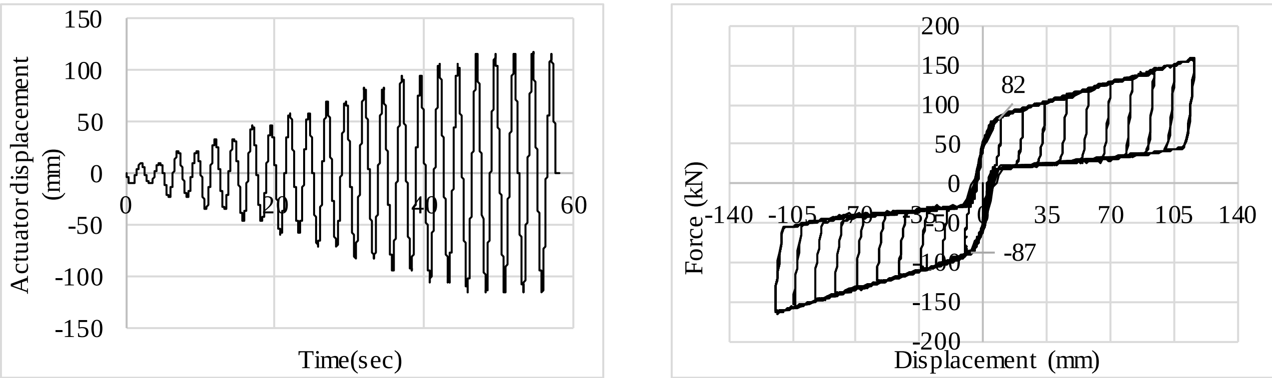
Figure 10. Comparison of the joint component test result and the estimated response

Frame dynamic test results

After the joint component tests, all components of the frame were erected and the joints were installed on the frame. Protection frames comprising of columns, beams, and props were sitting with 6 mm distance from the main frame on both sides in order to guide the main frame, minimize the lateral movements and vibrations during dynamic loading, and meet the safety requirements of the lab. Figure 11 shows the erected main frame and the protection frame ready to be tested.

Figure 11. The erected main frame and the protection frame ready to be tested

The dynamic loading protocol for this test was adopted from the seismic provisions of ASCE 7-10 [20] and AISC 341-10 [21] for BRBs and general dampers. The obtained loading protocol is displayed in Figure 12 (a). This loading protocol was calibrated to match the maximum velocity capacity of the actuator.



(a) (b)

Figure 12: (a) dynamic loading protocol with frequency of 0.4 Hz at the maximum displacement of 120 mm, (b) response of the frame under dynamic loading protocol

Then the frame was tested under this loading protocol and Figure 12 (b) depicts the corresponding response. This response demonstrates a stable, self-centering, energy-dissipative response under dynamic loading while all of the components are within their elastic range.

CONCLUSION

In this research, a new resilient tension-only brace has been introduced where 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 the 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. Firstly, the performance of the RSFJ has been experimentally verified on the component level and then dynamic full-scale experimental tests have been conducted 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.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of the Ministry of Business, Innovation and Employment (MBIE) of New Zealand.

REFERENCES

[1] A. Filiatrault and R. Tremblay, “Design of tension-only concentrically braced steel frames for seismic induced impact loading,” *Eng. Struct.*, vol. 20, no. 12, pp. 1087–1096, 1998.
[2] C. Durucan and M. Dicleli, “Analytical study on seismic retrofitting of reinforced concrete buildings using steel braces with shear link,” *Eng. Struct.*, vol. 32, no. 10, pp. 2995–3010, 2010.
[3] M. Badoux and J. O. Jirsa, “Steel bracing of RC frames for seismic retrofitting,” *J. Struct. Eng.*, vol. 116, no. 1, pp. 55–74, 1990.
[4] L. Di Sarno and G. Manfredi, “Seismic retrofitting with buckling restrained braces: Application to an existing non-ductile RC framed building,” *Soil Dyn. Earthq. Eng.*, vol. 30, no. 11, pp. 1279–1297, 2010.
[5] F. J. Molina, S. Sorace, G. Terenzi, G. Magonette, and B. Viaccoz, “Seismic tests on reinforced concrete and steel frames retrofitted with dissipative braces,” *Earthq. Eng. Struct. Dyn.*, vol. 33, no. 15, pp. 1373–1394, 2004.
[6] J. A. Pincheira and J. O. Jirsa, “Seismic response of RC frames retrofitted with steel braces or walls,” *J. Struct. Eng.*, vol. 121, no. 8, pp. 1225–1235, 1995.
[7] F. M. Mazzolani, G. Della Corte, and M. D’Aniello, “Experimental analysis of steel dissipative bracing systems for seismic upgrading,” *J. Civ. Eng. Manag.*, vol. 15, no. 1, pp. 7–19, 2009.
[8] L. Di Sarno and A. S. Elnashai, “Bracing systems for seismic retrofitting of steel frames,” *J. Constr. Steel Res.*, vol. 65, no. 2, pp. 452–465, 2009.
[9] L. Di Sarno and A. S. Elnashai, “Innovative strategies for seismic retrofitting of steel and composite structures,” *Prog. Struct. Eng. Mater.*, vol. 7, no. 3, pp. 115–135, 2005.
[10] P. Zarnani and P. Quenneville, “A Resilient Slip Friction Joint,” 708334, 2015.
[11] A. Hashemi, P. Zarnani, R. Masoudnia, and P. Quenneville, “Seismic resistant rocking coupled walls with innovative Resilient Slip Friction (RSF) joints,” *J. Constr. Steel Res.*, vol. 129, pp. 215–226, 2017.
[12] P. Zarnani, A. Valadbeigi, and P. Quenneville, “Resilient slip friction (RSF) joint: A novel connection system for seismic damage avoidance design of timber structures,” in *World Conf. on Timber Engineering WCTE2014, Vienna Univ. of Technology, Vienna, Austria*, 2016.
[13] A. Hashemi, P. Zarnani, A. Valadbeigi, R. Masoudnia, and P. Quenneville, “Seismic resistant cross laminated timber structures using an innovative resilient friction damping system,” in *Proc. New Zeal. Soc. Earthq. Eng. Conf.(NZSEE), Christchurch, New Zeal., Christchurch*, 2016.
[14] A. Hashemi, P. Zarnani, F. M. Darani, A. Valadbeigi, G. C. Clifton, and P. Quenneville, “Damage Avoidance Self-Centering Steel Moment Resisting Frames (MRFs) Using Innovative Resilient Slip Friction Joints (RSFJs),” in *Key Engineering Materials*, 2018, vol. 763, pp. 726–734.
[15] A. Hashemi, F. Darani, M. Yousef-biek, B. Zaboli, G. C. Clifton, P. Zarnani, and P. Qunneville, “Seismic performance of Resilient Slip Friction Joint (RSFJ) brace with collapse prevention mechanism,” *NZSEE Conf. Auckl.*, 2018.
[16] CSi, “SAP2000, Structural Software for Analysis and Design.” 2016.
[17] “NZS 1170.5: 2004 Structural Design Actions Part 5: Earthquake actions–New Zealand,” *Wellington, New Zealand: Standards New Zealand*. 2004.
[18] “NZS 3404: Part 1: 1997 Steel Structures Standard,” *Wellington, New Zealand: Standards New Zealand*. 2007.
[19] A. Hashemi, H. Bagheri, F. M. Darani, S. M. M. Yousef-Beik, P. Zarnani, and P. Quenneville, “An example procedure for preliminary sizing of Resilient Slip Friction Joints (RSFJS) in seismic resistant structures,” *SESOC J.*, vol. 31, no. 2, p. 44, 2018.
[20] ASCE/SEI 7-10, “Minimum Design Loads for Buildings and Other Structurtes,” *Am. Soc. Civ. Eng. Struct. Eng. Inst.*, 2010.
[21] AISC 341-10, “Seismic Provisions for Structural Steel Buildings,” *Chicago, Am. Inst. Steel Constr.*, 2010.