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Resilient Slip Friction Joint (RSFJ): A damage avoidance technology for seismic-proofing new and existing buildings

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ABSTRACT

With a clear global increase in frequency and impact of seismic events, there is an ever-growing need to ensure public safety, minimize fatality risk and economic impact of seismic events. Damage in recent major earthquakes has resulted in efforts by engineers to develop seismic-proofing technologies that not only provide life-safety, but also aim to minimize the damage so that the buildings could be reoccupied quickly with minimal business interruption. There are two key characteristics that need to be provided for a structure to be able to resist the earthquake loads with minimum damage: (1) energy dissipation, and (2) self-centering. Latest research showed that if the lateral residual drift of the structure is more than 0.15%, the structural members need to be re-aligned after or the structure needs to be demolished. Most of the self-centering systems include inelastic members that provide damping and an external mechanism (such as post-tensioned elements) to provide the self-centering behavior which the integration of these two categories is not necessarily economical and may require a complex configuration. The innovative Resilient Slip Friction Joint (RSFJ) technology that has recently been introduced to the construction industry is a friction-based damping device with a special configuration that can produce a flag-shape hysteresis. It can be used in various applications including (but are not limited to) shear wall hold-downs, tension-compression braces, tension-only braces and moment resisting frames. The philosophy of design is that the inelastic behavior of the structure is provided by the geometrically nonlinear behavior of the RSFJs and the rest of the structural members remain elastic. The RSFJ also has a built-in collapse-prevention secondary fuse which will be activated when the earthquake forces are larger than the design loads.

This paper aims to introduce the RSFJ technology and also to report on the latest related developments. The results and discussions about the conducted experimental tests are provided. The experiments include quasi-static joint component tests and full-scale demonstration tests. The results confirmed the excellent seismic performance of the technology in terms of energy dissipation, self-centering characteristic and the predictable system behavior. Moreover, the paper addresses the techniques that this technology can be used for seismic proofing of the existing buildings.

Keywords: resilience, seismic-proofing, friction, self-centering, residual drift.

INTRODUCTION

Friction based energy dissipation devices has already been proven to be one of the most efficient solutions amongst the passive damping systems to control the seismic performance of the structure and decrease the damage during and after earthquakes. These devices that were originally developed by Pall et al. for the steel braced frames and concrete panels [1-2] are also known to be cost efficient considering the simplicity of installation and the configuration used for the assembly. Popov et al. later introduced the symmetric slotted bolted connection for steel moment frames which dissipates energy through frictional sliding while producing equilateral load-deformation curves in tension and compression [3]. Clifton et al. proposed the asymmetric Sliding Hinge Joint (SHJ) for steel moment resisting frames which had non-rectangular yet stable hysteretic behavior [4]. Regardless of the good performance of these devices and their large energy dissipation ratio, the residual displacements after the seismic event has always been a concern for the structures equipped with friction devices. More to the point, studies of Erochko el al. [5] demonstrated that residual drifts more than 0.5% in structures might result in a significant loss in the building from structural and economical points of view. They asserted to the fact that 0.5% of residual drift can be considered as a total loss level of the structure in a way that replacing the building is more economical than repairing it. As a result, self-centering structural solutions have been developed by researchers and engineers to minimize the post-event residual displacements. Tremblay et al. [6] and Christopoulos et al. [7] introduced and developed the Self-Centering Energy Dissipative (SCED) brace that consists of steel bracing elements and friction energy absorption members coupled with a simple self-centering mechanism using pre-stressed steel tendons. The brace is configured in a way that the tendons are elongated when the brace is under tension or compression loads, resulting in a symmetrical flag-shaped hysteresis response. Zhu and Zhang [8] introduced a special type of bracing system named Self-centering Friction Damping Brace (SFDB) for the application in CBFs. The SFDB is a passive energy dissipation device with a self-centering mechanism made of stranded super-elastic Nitinol wires and a friction-based energy absorption mechanism. The PRESSS system for reinforced concrete structures [9] and Pres-Lam system [10] for timber structures are other examples of previously developed self-centering systems where post-tensioned tendons/rods were used to bring back the structure at the end of the seismic event.

Nevertheless, as mentioned, almost all of the developed self-centering concepts rely on an external mechanism to provide the re-centering behavior and one or a group of inelastic members to provide energy dissipation. Integration of these two categories is not necessarily economical given it most likely requires a complex configuration. The ideal solution could be a single device that can be installed in different locations of the structure and can provide both requirements (energy dissipation and self-centering) with no special configuration or no complex arrangement.

THE RESILIENT SLIP FRICTION JOINT (RSFJ)

The innovative Resilient Slip Friction Joint (RSFJ) [11] technology has recently been developed and introduced to the New Zealand construction industry. This damage avoidance technology that already has been implemented in two real projects, not only aims to provide life safety, but also to minimize the earthquake-induced damage so that the building can be reoccupied quickly with minimum business disruption. The RSFJ device provides self-centering behavior and seismic energy dissipation in one compact package. It also includes a built-in collapse prevention secondary fuse function that adds more resiliency to the system in case of a seismic event larger than the design level. Hashemi et al. [12] experimentally verified the flag-shaped hysteresis and the self-centering characteristic of the RSFJ. The conducted experiments showed that this device also has different adjustable variables in which almost any desirable flag-shaped hysteresis is achievable.

Figure 1 shows the components and the assembly of the RSFJ. In this joint, the energy is dissipated by frictional sliding of the moving plates while the specific shape of the ridges combined with the use of disc springs provide the necessary self-centering behavior. The angle of the ridges is specified in a way that at the time of unloading, the restoring force induced by the elastically compacted disc springs is greater than the resisting frictional force between the sliding parts. Thus, the elastic force of the discs re-centers the slotted sliding plates to their original stationary position. Figure 1(c) shows the device at rest when the disc springs are partially compacted. When the force applied to the joint overcomes the resistance between the clamped plates, the middle plates start to move and the cap plates start to expand until the joint is at the maximum deflection and the disc springs are flat (see Figure 1(d)).

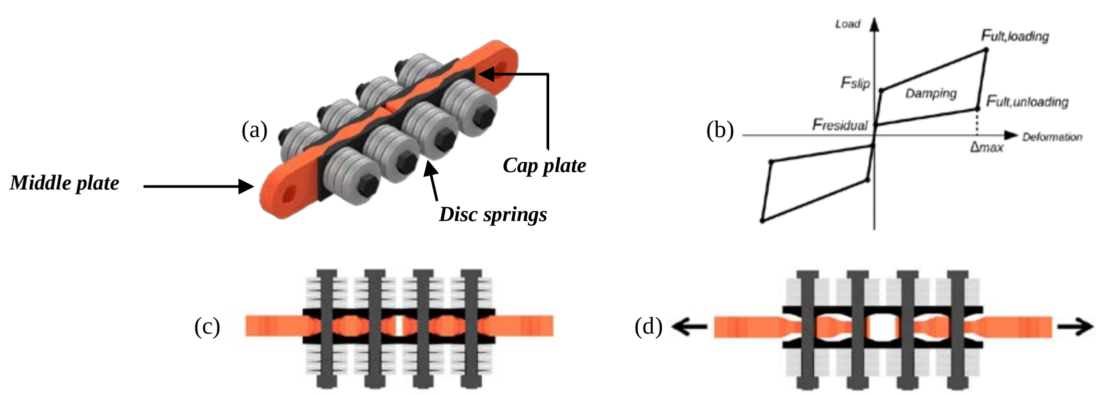

Figure 1. Resilient Slip Friction Joint (RSFJ): (a) assembly, (b) hysteresis, (c) the joint at rest, (d) the joint at the maximum deflection within its elastic response

Figure 1(b) displays the load-deformation behavior for the RSFJ. The slip force (F_{slip}) and the residual force ($F_{residual}$) in the joint can respectively be determined by Eq. (1) and Eq. (2) where $F_{b,pr}$ is the clamping force in the bolts, n_b is the number of bolts, θ is the angle of the ridges, μ_s is the static coefficient of friction and μ_k is the kinetic coefficient of friction. The ultimate force in loading ($F_{ult,loading}$) and unloading ($F_{ult,unloading}$) can be calculated by substituting μ_s and $F_{b,pr}$ in Eq. (1) and Eq. (2) with μ_k and $F_{b,u}$, respectively. It should be noted that the initial stiffness of the RSFJ (the stiffness before F_{slip} in Figure 1(b)) is related to elastic stiffness of the sliding plates and of any other component connected to the RSFJ.

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

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

Figure 2 shows a part of the RSFJ component testing program. It can be seen that the RSFJ provide a stable load-deformation behavior where the joint maintains its stiffness and strength over numerous cycles of loading and unloading. The observed flag-shaped hysteresis clearly exhibits the self-centering behavior without relying on any external mechanism.

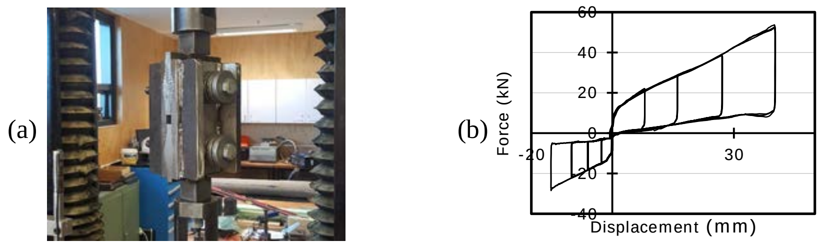

Figure 2. RSFJ component test: (a) test setup, (b) results of the cyclic tests

LATERAL LOAD RESISTING SYSTEMS DEVELOPED WITH THE RSFJ TECHNOLOGY

The RSFJ can be used in various applications including (but are not limited to) shear wall/rocking column hold-downs, tension-compression braces, tension-only braces and moment resisting frames. The philosophy of design is that the inelastic behavior of the structure is provided by the geometrically nonlinear behavior of the RSFJs and the rest of the structural members remain elastic. This section describes some of the developed concepts including the conducted experimental tests and results.

RSFJ hold-downs for rocking Cross Laminated Timber (CLT) shear walls

Figure 3 shows the concept and the test setup related to a rocking CLT shear wall with RSFJ hold-downs. As can be seen, two identical RSFJs were installed in the notches at the bottom corner of the CLT panel. Each joint consists of two slotted middle plate and two cap plates. The RSFJs were designed and fabricated to be able to accommodate a maximum displacement of 65mm in tension and 15mm in compression (corresponding to 3.5% of lateral drift). The tested CLT panel had five 40 mm thick layers made of MSG8 timber (200mm of thickness in total). Each device had two bolts and 11 disc springs per bolts per side. The springs used had a maximum load capacity of 110 kN and a maximum displacement capacity of 1.5 mm at flat state. The loading protocol displayed in Figure 4(a) was applied to the wall at the height of 3350 mm.

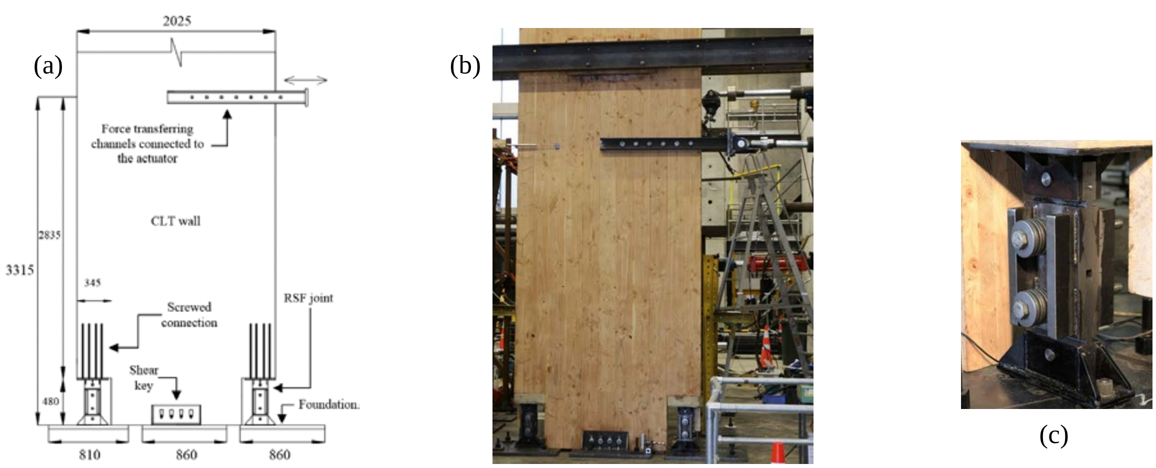

Figure 3. Experimental test of rocking CLT wall with RSF joints: (a) general arrangement, (b) test setup, (c) RSFJ

Eight tests in total were carried out on the wall with different pre-stressing ratios for the RSFJs. No damage was observed to the wall with no evidence of deterioration in strength or stiffness of the RSFJs. Figure 4(b) shows the typical hysteresis for the system as the representative for rest. The slip force was approximately 50% of the maximum force. The flag-shaped hysteresis in Figure 4(b) clearly highlights the self-centering behavior of the tested wall that was achieved without relying on any external gravity load other than the self-weight of the CLT panel.

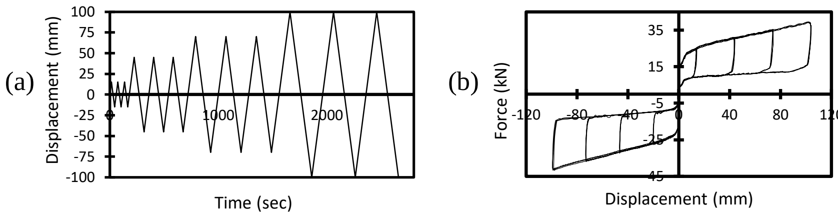

Figure 4. Test results: (a) applied load-schedule, (b) load-deformation behavior

RSFJ hold-downs for rocking Laminated Veneer lumber (LVL) columns with out-of-plane performance

Similar to the concept described above, RSFJs can also be used as hold-down connectors for rocking columns. It should be noted that given the seismic performance of the systems described comes from the RSFJs and the rest of the members stay in their elastic range, the performance of the systems is independent from the material used for the main structural members. The only difference would be the structural detail used to connect the RSFJs to the main structural members.

Figure 5 shows the configuration of the full-scale experimental test carried out on a rocking Laminated Veneer Lumber (LVL) column with RSFJ hold-downs. In this case, high strength rods were used to attached the RSFJs to the rocking column and the steel foundation plate. A similar detail can be used in case of a rocking concrete shear wall with anchor bolts embedded in the wall panel at the top of the RSFJ and in the foundation at the bottom. As can be seen, a bi-directional test is performed to verify in- and out-of-plane performance of the column. Figure 5(c) and 5(d) show the experimental results. It can be seen that a stable flag-shaped hysteresis is achieved for up to 2.7% lateral drift without relying on any external mechanism. The applied load protocol was two full cycles at the ultimate lateral drift. Moreover, the out-of-plane test results shown in Figure 5(b) demonstrates a nearly elastic behavior up to 2.7% lateral drift. It is also observable that the system has an out-of-plane resistance that is almost one third of the resistance of the system in the primary direction. This extra damage-free out-of-plane resistance can be an advantage for the designer to optimize the size and capacity of the RSFJs in the structure. Alternatively, pins and swivel bearings can be used to attach the RSFJs to the bottom foundation plates to eliminate the out-of-plane resistance and provide the required displacement compatibility.

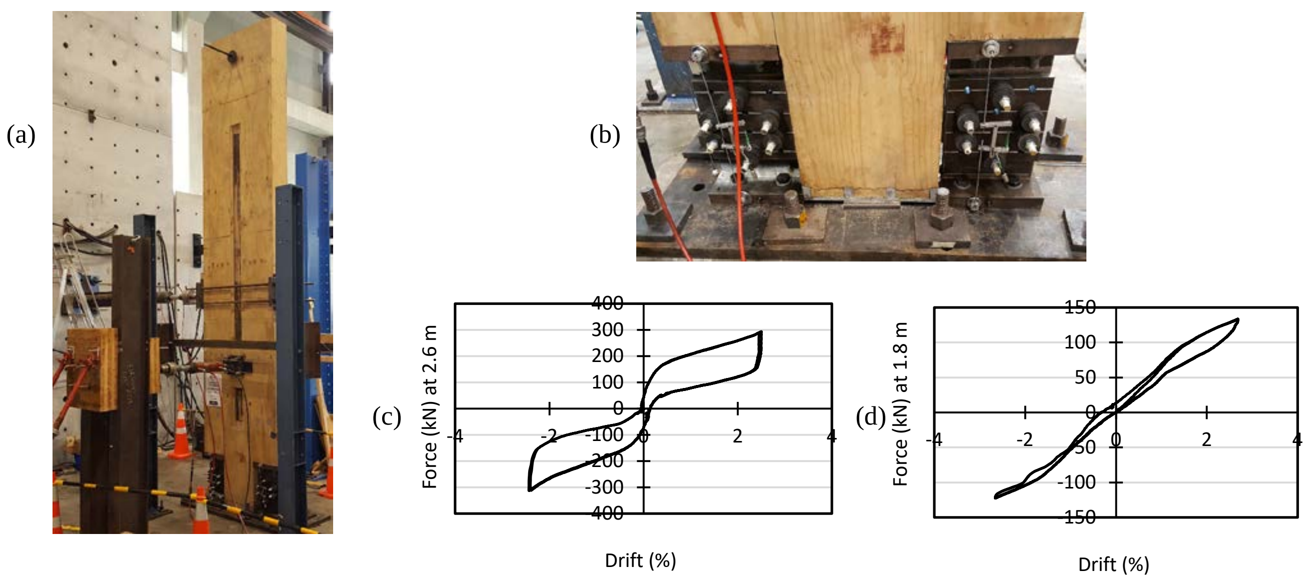

Figure 5. Full-scale testing of the rocking LVL column with RSFJ hold-downs: (a) test setup, (b) RSFJ hold-downs, (c) bi-directional test results, (d) out-of-plane test results

RSFJ tension/compression brace

Figure 6 schematically shows the RSFJ tension/compression brace concept. This bracing system includes a RSFJ acting in tension and compression (providing energy dissipation and self-centering) attached to a conventional steel section. The brace can be connected to the frame structure using conventional solutions such as pinned, welded or bolted connections. Similar to the other bracing systems, depending on the rotational stiffness of the brace, the global buckling can considerably affect the performance when the brace is in compression. Thus, an analytical model is developed to the predict the different instability modes related to the self-centering braces and to identify the possible failure modes. Accordingly, an experimental program was performed on a small scale RSFJ brace and based on the results, it was concluded that there are two main differences between the buckling of self-centering braces and conventional ones. The first and foremost is that these braces are prone to buckling in both loading and unloading phases mainly because in the unloading process, there is still a compressive restoring force, which can potentially cause buckling. Another difference is that the buckling of the self-centering braces possesses a nonlinear elastic behavior implying that not only the braces may buckle during the different phases of loading, but also the buckling itself is an elastic type with no residual displacement or permanent damage. The reader is referred to [13] for more information about the concept including the developed equations, small scale experimental tests (Figure 6(a)) and results.

To restrain the RSFJ and prevent the global buckling of the brace from happening, a telescopic mechanism is proposed where the RSFJs are attached to the flanges of a steel hollow section and as per Figure 6(b) and another steel section is considered at the other end which the inner section slides inside when the brace is in compression. With this detail, the RSFJs act in pure tension/compression during loading and unloading providing the desired flag-shaped load-slip behavior.

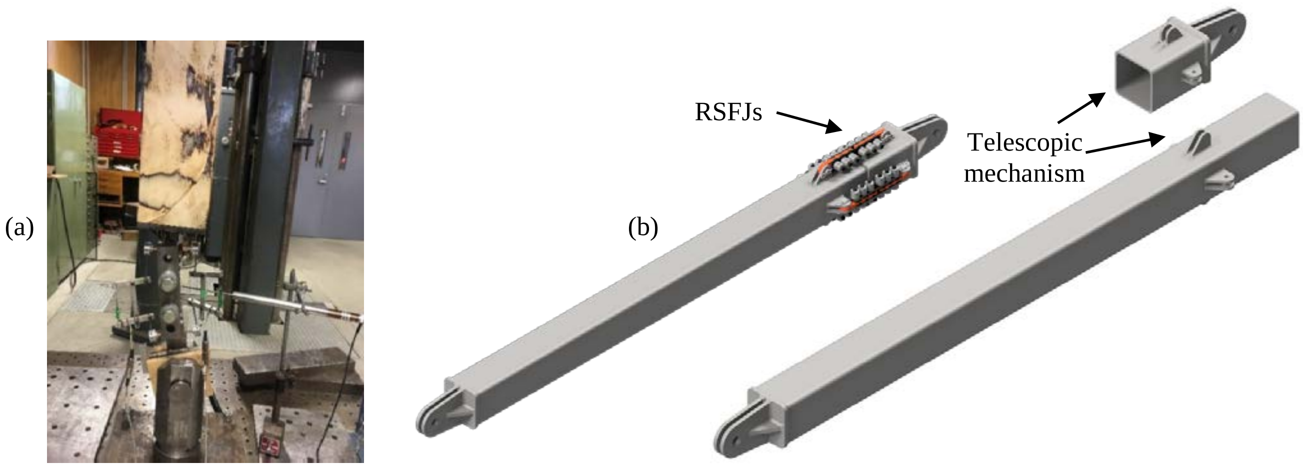

Figure 6. RSFJ brace: (a) experimental test, (b) telescopic mechanism

STRUCTURAL PERFORMANCE OF THE BUILDNIGS DESIGNED WITH RSFJS

This section briefly describes the numerical modelling and analysis of a steel frame with RSFJ braces. The flag-shaped hysteresis of the RSFJ can be modelled using the “Damper – Friction Spring” link element in SAP2000 and ETABS providing the design parameters are properly calibrated [14].

Figure 7(a) shows the specifications of the considered prototype steel frame including the geometric properties and the frame sections. Seismic masses of 17.8, 16.9, 10 tons were assigned to level one, levels two to four and level five, respectively. The structure was analysed using the Displacement Based Design (DBD) approach considering 15% hysteretic damping resulting in 620 kN of base shear. The design level forces (Ultimate Limit State (ULS)) in the RSFJ braces were accordingly determined. The slip threshold for the RSFJs are specified as 50% of the ultimate capacity. It should be emphasized that the specified slip thresholds for the RSFJs should comply with the Serviceability Limit State (SLS) forces. In other words, the joints should only slip after the applied load exceeds the serviceability design force to avoid undesired shakings in the structure. Table 1 shows the calculated hysteresis for the RSFJ braces. Note that for this case, the RSFJs are designed to maintain their stiffness up to 3% of lateral drift. From the pushover curve shown in Figure 7(b), it is apparent that the systems with RSFJ braces can easily meet this criterion.

In addition to the static pushover analysis, non-linear dynamic time-history simulations were carried out for the prototype frame to further investigate the performance of the system. A suite of four commonly used ground motions was selected for the simulations. The ground motions were scaled for the design return period (500 years) and the Maximum Considered Event (MCE) return period (2500 years) with soil type C in Christchurch, New Zealand.

Table 1. Specifications of RSFJ braces.

Location	*Fslip* (kN)	$F_{ult,loading}$ (kN)	$F_{ult,unloading}$ (kN)	$F_{residual}$ (kN)	Displacement (mm)
Level 5	100	200	82	43	100
Level 4	200	400	100	52	100
Level 3	270	540	134	78	100
Level 2	320	640	210	115	100
Level 1	360	715	268	140	100

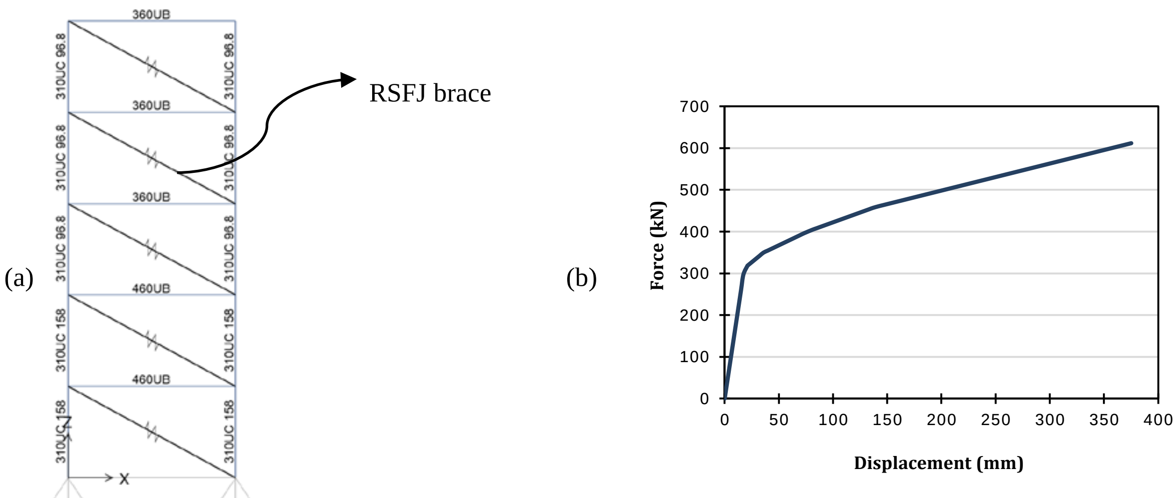

Figure 7. Numerical modelling of the prototype steel frame with RSFJ braces: (a) numerical assembly (b) push-over curve

Figure 8 displays the load-deformation behavior of the first story RSFJ brace in two of the MCE events. It can be seen that the RSFJ braces maintain their stable flag-shaped hysteresis. It should be noted that the residual displacements was zero for all of the cases (eight analyzed cases) which clearly demonstrates a fully self-centering behavior. Figure 9(a) shows the results of the time-history simulations. It can be seen that for all of the ULS and MCE events, the peak roof responses are considerably below the New Zealand code-prescribed limits (2.5% of lateral drift for the design loads and 3.75% for MCE) which confirms the efficiency of this system. In other words, the RSFJ bracing system offers predictable behavior with no post-event issues. Figure 9(b) shows the base shears. It is apparent that for all of the events, the base shear is under the 620 kN determined using the DBD procedure. More to the point, since the internal loads in the system are always enclosed within the RSFJ curves (regardless of the number of loading/unloading cycles), considerable savings can be made by reducing the size of the beams, columns and other structural members when compared with the systems that are involved with increased inelastic loads due to yielding of the members. Overall, the results of this preliminary numerical modelling demonstrated the clear potential of the RSFJ brace as an efficient substitute for BRBs, viscous dampers and conventional bracing systems. The RSFJ brace also is very convenient for seismic retrofitting existing buildings given the conventional braces can be cut and modified so the RSFJs and the jacket can be added to the existing brace body.

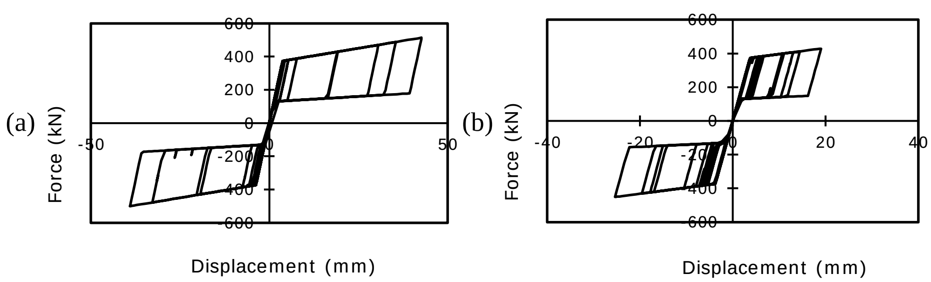

Figure 8. Numerical results: (a) RSFJ brace hysteresis for Kobe (MCE), (b) RSFJ brace hysteresis for Northridge (MCE)

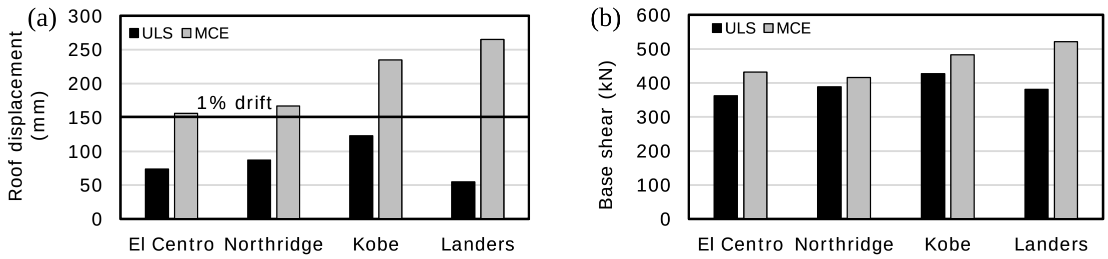

Figure 9. Numerical results: (a) roof response histories, (b) base shears

THE SECONDARY COLLAPSE-PREVENTION FUSE OF THE RSFJ

The design of the RSFJ is aimed for all parts in the RSFJ itself to remain elastic and the required inelastic characteristic is only provided by controlled frictional sliding in the RSFJ. However, with the aim of collapse prevention in cases that the applied forces are higher than the design seismic loads, a collapse-prevention secondary fuse is considered within the body of the RSFJ. When the RSFJ reaches its peak force/displacement capacity and the ridges are locked, the clamping bolts (or rods) start to yield in tension. The plastic elongation of the bolts provides additional travel distance for the RSFJ making it able to provide a ductile behavior even more than the collapse limit state of the structure. This means for example, when the RSFJ is at its design seismic loads (usually corresponding to 2.5% of inter-story drift), a ductile behavior can be provided up to 1.5 times of the displacement demand which could be close to the MCE (usually around 4% of inter-story drift).

The specifications of the clamping bolts (or rods) specify the behavior of the RSFJ after this fuse is engaged. Figure 10(a) shows the characteristics of the clamping bolts in which $k_{fuse,plastic}$ is the effective plastic stiffness of the bolts after yielding up to their ultimate force ($F_{ult,fuse}$) before necking happens. In the RSFJ, the disc springs are fully compressed at the maximum capacity of the joint ($F_{ult,loading}$). At this stage, the clamping bolts start to yield and that provides more displacement capacity for the joint yet reduces the design slip force in the RSFJ (F_{slip}) in each cycle. Note that the self-centering behavior is not compromised.

Figure 10 shows the experimental results for the RSFJ secondary fuse tests. Before testing the RSFJ assembly itself, a series of component tests were conducted on the rod specimens to extract their exact characteristics. Figure 10(a) shows the experimental load-deformation curve for one of the rods as the representative for the rest. As can be seen, the rod has $F_{fuse,y}$=145 kN and $F_{fuse,ult}$ = 165 kN, k_{fuse}=1835 N/mm and 5% elongation considering its initial length. Figure 10(b) displays the results of the cyclic test on the RSFJ before and after the collapse-prevention secondary fuse is engaged. The joint was designed to lock at 8 mm of deflection. The top red rectangle in Figure 10(b) highlights the region where the rods are yielding. It can be seen that the analytically obtained effective stiffness of the RSFJ [15] ($K_{rsfj,fuse}$) after locking is consistent with the experimental data. Furthermore, it is evident that the slip force is decreased after the fuse is activated. This is owing to the plastic elongation in the rods which reduces the pre-stressing force in the disc springs.

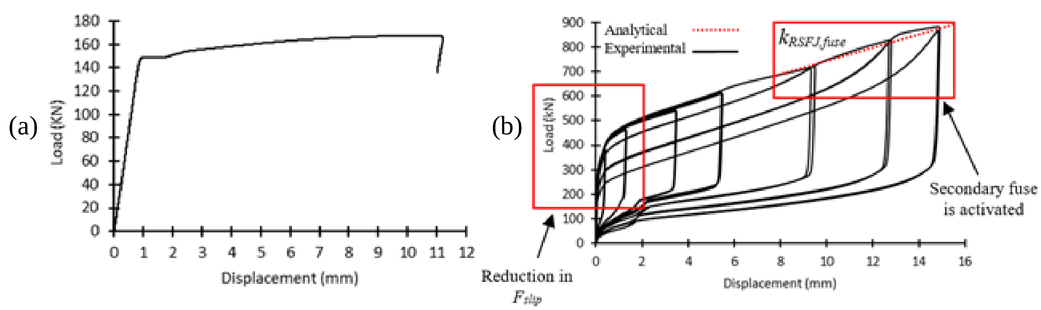

Figure 10. Experimental results of the RSFJ with the collapse prevention fuse: (a) load-deformation curve of the M18 rod grade 8.8, (b) load-deformation curves of the RSFJ

CONCLUSIONS

The innovative Resilient Slip Friction Joint (RSFJ) technology that has recently been introduced to the construction industry is a friction-based damping device with a special configuration that can produce a flag-shape hysteresis resulting in a self-centering behavior for the structure. It can be used in various applications including (but are not limited to) shear walls, tension-compression braces, tension-only braces and moment resisting frames. The philosophy of design is that the inelastic behavior of the structure is provided by the geometrically nonlinear behavior of the RSFJs and the rest of the structural members remain elastic. The RSFJ also has a built-in collapse-prevention secondary fuse which will be activated when the earthquake force is larger than the design force. With this over-strength mechanism activated, the clamping bolts in the device will yield in pure tension and more axial deformation will be provided while the self-centering behavior is maintained.

This paper introduces the RSFJ technology and also reports on the latest developments on the application including the concepts developed and the experimental test results. The experiments include quasi-static and dynamic joint component testing and full-scale demonstration tests confirmed the excellent seismic performance of the technology in terms of energy dissipation, self-centering characteristic and predictable system behavior. Furthermore, the numerical modelling of a five-story steel frame with RSFJ braces showed the good and predictable seismic performance for the system.

Moreover, it was showed that by using this technology, the seismic performance of the buildings would be material independent given the performance of the systems comes from the RSFJs.

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REFERENCES

[1] A. S. Pall, C. Marsh, and P. Fazio, "Friction joints for seismic control of large panel structures," *PCI J.*, vol. 25, no. 6, pp. 38–61, 1980.

[2] P. Baktash, C. Marsh, and A. Pall, "Seismic tests on a model shear wall with friction joints," *Can. J. Civ. Eng.*, vol. 10, no. 1, pp. 52–59, 1983.

[3] E. P. Popov, C. E. Grigorian, and T.-S. Yang, "Developments in seismic structural analysis and design," *Eng. Struct.*, vol. 17, no. 3, pp. 187–197, 1995.

[4] G. C. Clifton, G. A. MacRae, H. Mackinven, S. Pampanin, and J. Butterworth, "Sliding hinge joints and subassemblies for steel moment frames," in *Palmerston North, New Zealand: Proc of New Zealand Society for Earthq Eng Conf*, 2007.

[5] J. Erochko, C. Christopoulos, R. Tremblay, and H. Choi, "Residual drift response of SMRFs and BRB frames in steel buildings designed according to ASCE 7-05," *J. Struct. Eng.*, vol. 137, no. 5, pp. 589–599, 2010.

[6] R. Tremblay, M. Lacerte, and C. Christopoulos, "Seismic response of multistory buildings with self-centering energy dissipative steel braces," *J. Struct. Eng.*, vol. 134, no. 1, pp. 108–120, 2008.

[7] C. Christopoulos, R. Tremblay, H.-J. Kim, and M. Lacerte, "Self-centering energy dissipative bracing system for the seismic resistance of structures: development and validation," *J. Struct. Eng.*, vol. 134, no. 1, pp. 96–107, 2008.

[8] S. Zhu and Y. Zhang, "Seismic analysis of concentrically braced frame systems with self-centering friction damping braces," *J. Struct. Eng.*, vol. 134, no. 1, pp. 121–131, 2008.

[9] M. J. N. Priestley, S. Sritharan, J. R. Conley, and S. Pampanin, "Preliminary results and conclusions from the PRESSS five-story precast concrete test building," *PCI J.*, vol. 44, no. 6, pp. 42–67, 1999.

[10] F. Sarti, A. Palermo, and S. Pampanin, "Development and Testing of an Alternative Dissipative Posttensioned Rocking Timber Wall with Boundary Columns," *J. Struct. Eng.*, p. E4015011, 2015.

[11] P. Zarnani and P. Quenneville, "A Resilient Slip Friction Joint.", NZ IP Office, Patent No. WO2016185432A1, 2015.

[12] 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, 2017.

[13] S. M. M. Yousef-Beik, H. Bagheri Mehdi Abadi, P. Zarnani, A. Hashemi, and P. Quenneville, "Damage-avoidance Timber Brace using a Self-centring Friction Damper," *Pacific Conf. Earthquke Eng. (PCEE2019), Auckland, New Zeal.*, 2019.

[14] A. Hashemi, P. Zarnani, R. Masoudnia, and P. Quenneville, "Experimental testing of rocking Cross Laminated Timber (CLT) walls with Resilient Slip Friction (RSF) joints," *J. Struct. Eng.*, vol. 144, no. 1, pp. 04017180-1 to 04017180-16, 2017.

[15] 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.