17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

A LOW-DAMAGE STEEL STRUCTURE USING RESILIENT SLIP FRICTION JOINT FOR A FULL-SCALE SHAKING TABLE TEST

H. Bagheri[(1)], A. Hashemi[(2)], P. Zarnani[(3)], P. Quenneville[(4)], Z. Yan[(5)], G.C. Clifton[(6)], G.A. MacRae[(7)] R. Dhakal[(8)], X. Zhao[(9)], L. J. Jia[(10)], P. Xiang[(11)]

[(1)] *PhD candidate, The University of Auckland, hbag051@aucklanduni.ac.nz*
[(2)] *Postdoctoral research fellow, The University of Auckland, a.hashemi@auckland.ac.nz*
[(3)] *Lecturer, Auckland University of Technology, pouyan.zarnani@aut.ac.nz*
[(4)] *Professor, The University of Auckland, p.quenneville@auckland.ac.nz*
[(5)] *PhD candidate, The University of Auckland, yzhe760@aucklanduni.ac.nz*
[(6)] *Associate professor, The University of Auckland, c.clifton@auckland.ac.nz*
[(7)] *Associate professor, University of Canterbury, gregory.macrae@canterbury.ac.nz*
[(8)] *Professor, University of Canterbury, rajesh.dhakal@canterbury.ac.nz*
[(9)] *Professor, Tongji University, x.zhao@tongji.edu.cn*
[(10)] *Assistant professor, Tongji University, lj_jia@tongji.edu.cn*
[(11)] *Associate professor, Tongji University, p.xiang@tongji.edu.cn*

Abstract

The objective of this study is to present the design and numerical analysis for some structural applications of Resilient Slip Friction Joint (RSFJ) as low-damage structural systems in a steel structure for shaking table tests. These structural applications include tension-only and tension/compression braced frames as well as moment resisting frame (MRF). During seismic events deformation compatibility and members interaction, members and connection in- and out-of-plane behavior, and dynamic loading are of concern. Following this research, the design of the mentioned RSFJ structural systems will be illustrated. A full-scale three-dimensional three-story steel structure is designed using the equivalent static method. The structure is assumed to be located in Wellington, New Zealand on a soil class C with an importance level of two including two bays in the longitudinal direction and one bay in the transverse direction and total planar dimensions of 7.25 by 4.75 m and the inter-story height of 3 m. Then, the RSFJs are designed in different applications using nonlinear push-over analysis including joints nonlinearity. Then, nonlinear time-history analysis (NLTHA) is undertaken to check the members and the RSFJs adequacy. One record is selected which acceptably matches the site target spectrum over the period range of interest and is scaled to serviceability limit state (SLS). The test is to happen at the International Joint Research Laboratory of Earthquake Engineering (ILEE), Shanghai, China. According to the design undertaken, a resilient structure is proposed with no need to replace any structural component which in turn can meet immediate occupancy requirements.

Keywords: seismic; full-scale; shaking table test; RSFJ; self-centring

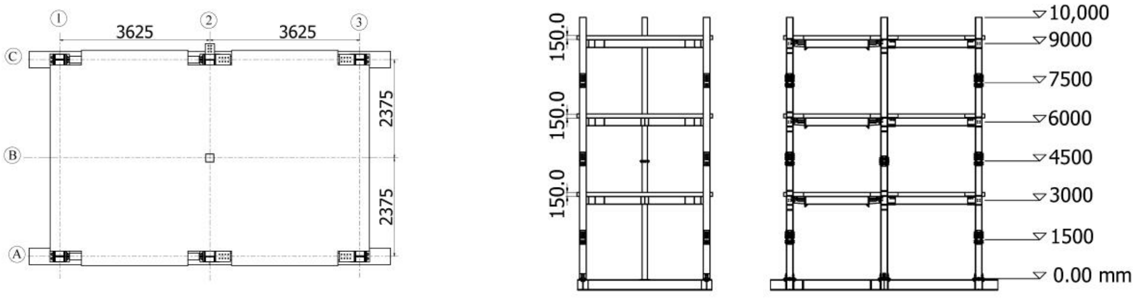
Introduction

The objective of this research is to present the design for a shaking table test on a three-dimensional full-scale steel structure secured with different applications of the RSFJ as no-damage seismic systems. The shaking table test can best simulate the effects of real earthquakes on real structures amongst different types of structural experiments. Such a test includes dynamic inertial effects, three-dimensional shaking and movements, deformation compatibility, interaction of structural/non-structural elements, and floor contribution to performance of the structural systems. As a long term goal of this research, the buildings secured with the considered structural system in this research help significantly move towards the requirements of having a resilient community with minimal/no monetary loss, which may arise from retrofitting, demolishing and rebuilding of structures, and no business interruptions and downtime. Applications of the RSFJ including tension-only brace, tension/compression brace, and MRF will be considered in this program in sequences by taking off one application's essential members and putting in next application's elements. An important index to characterize level of damage to a structure after an earthquake is the residual drift [1]. In the technical literature, different residual drift limits have been suggested for different levels of performance. Based on the research conducted by [2 and 3], if the residual drift is greater than 0.5%, the structure is potentially demolished taking into account human-feeling and safety considerations. [4] inspected multi-story steel structures after the Christchurch February 2011 earthquake and observed that in the Club Tower building located in Christchurch's central business district (CBD) with a residual drift of 0.1%, the lift shaft was not fully operational and needed realignment. As such, they concluded that the 0.3% drift limit for successful low damage building performance proposed by some is too high. In order to resolve the residual drift issue, various self-centring systems have been developed. The most common practice for these systems is to add post-tensioning rods and strands to conventional structural members in combination with supplemental source of damping that can be yielding component, viscous dampers or friction surfaces. This concept has been successfully adopted in seismic isolation systems [5], beam-to-column-connections [3 and 6], and bridges [7]. Moreover, newly developed smart materials such as shape memory alloy (SMA) are alternative solutions for providing self-centring capabilities to structures. [8] carried out shaking table test on a half-scale two-story steel moment frame using asymmetric friction connections (AFCs) at the column bases and beam ends. AFC is offered after symmetric friction connection (SFC) to remove the problem of beam end and overlying floor interaction as rotation occurs at the beam end. The results of their study indicated that the residual drifts were less than 0.2% for shaking intensities up to 3% peak inter-story drift; and even at peak inter-story drift of 6.5% the residual drift was 0.7%. [9] conducted experimental and numerical studies on a scaled steel frame with SMA braces as self-centring component. The post- yield stiffness ratio and equivalent viscous damping of the brace used in this research were 0.15 and 5% respectively which were derived from cyclic loading on the fabricated braces. In this research, a two-dimensional half-scale steel frame was connected through purely pinned connections to a mass simulation frame to simulate the inertial force. The experimental results showed that this system can withstand several strong earthquakes with very limited degradation; the steel frame suffered from limited damage but with zero residual deformation up to drift ratio of 2%. [10] conducted a shaking table test to confirm performance of the self-centring energy dissipation (SCED) braces in a real structure. The SCED brace has been introduced by [11] equipped with post-tensioned rods and additional source of frictional damping relying on a thin friction pad and sliding over a stainless steel surface. Finally, the tests results demonstrated that SCED braces prevented any residual drifts in the structure without any significant degradation due to wearing. The Resilient Slip Friction Joint (RSFJ) is recently invented by Zarnani and Quenneville [12] to resolve the potential residual displacement issue in structures after a major seismic event and also to provide damping in a single device. Through the past studies, the governing equations of the joint have been developed [13] and the joint has been tested in different structural applications to bring resiliency to their seismic performance including steel tension-only brace [14] which can be used for retrofitting applications as well (Bagheri et al. 2018), rocking Cross Laminated Timber (CLT) shear wall [13], pre-cast concrete shear wall [16], timber brace including the stability studies of the joint and brace body [17]. Also, study of the steel MRF and design of the test set-up have been given in [18]. The rotational version of the

RSFJ in order to enhance the displacement capacity has been developed by [19] which has also been studied into rocking concrete shear walls [20]. [21] gives a proposed design procedure for design of tension-only RSFJ bracing system and [22] presents an equivalent ductility approach for designing structures with RSFJ. This research aims to present the structural design and numerical analysis for a full-scale steel structure shaking-table test incorporating three different structural applications of the RSFJ in steel structures including tension-only brace, tension-compression brace, and MRF.

ROBUST Test program

In order to experimentally demonstrate the latest research outcomes for RObust BUilding SysTems (ROBUST), a comprehensive joint experimental program of a full-scale three-dimensional steel structure shaking table test has been scheduled through collaboration of New Zealand and Chinese structural and earthquake engineering scholars/experts. The test is planned to occur at the (ILEE), Shanghai, China. The structure will have three stories with story height of 3 m and total planar dimensions of 7.25 by 4.75 m with two bays in the longer direction and one bay in the shorter. The structure includes column splices at midheight of columns in each story of the external transverse frames to make possible rocking action happening there. Also, a splice has been placed at the midheight of the central column of the structure which serves as a gravity column only. Figure 4 includes the plan and side views of the structure considered including dimensions.



(a) (b) (c)

Figure 1: (a) Plan, (b) transverse, and (c) longitudinal views of the test structure (mm)

The composite flooring system with trapezoidal steel deck and concrete on top, is considered for permanent load on the structure. In order to simulate the imposed load, additional mass blocks have been used for different stories which imposes a uniform load of 3.5kPa for the first and second floor and 4.7kPa for the third floor. To keep the integrity of the structure, a ring beam underlying all the columns is used. The summation of the permanent (concrete floors and members) and imposed loads (additional mass blocks) forms the seismic weight of the structure. Table 1 gives the seismic weight of the structure in different stories.

Table 1: Seismic weight of the structure in different stories

Level	**Height (m)**	**Seismic weight (kN)**
3	9	276

2	6	251
1	3	251
Total	N/A	779

The building is assumed to be located in Wellington (soil class C) with importance level of 2 and 5 km distant from the nearest fault. In the following sections, the design procedure for each concept have been given in which it is aimed to have a robust building up to MCE.

RSFJ MRF configuration

In this concept, the RSFJs are placed at the bottom flange of the beam and the positive and negative moments are provided through joints axial actions in tension and compression. The RSFJs are attached from one end to the column flange and from another end to end plates provided on the web sides of the beam. At the top flange, a pin connection is used in which the pin connects the beam web at the topmost point to a cleat. This concept is used in the longitudinal direction of the test structure and only in one bay while the other bay will have simple connections. The RSFJs are used in all stories. A view of the longitudinal frame of the structure including the RSFJ locations in the MRF concept is shown in Figure 2.

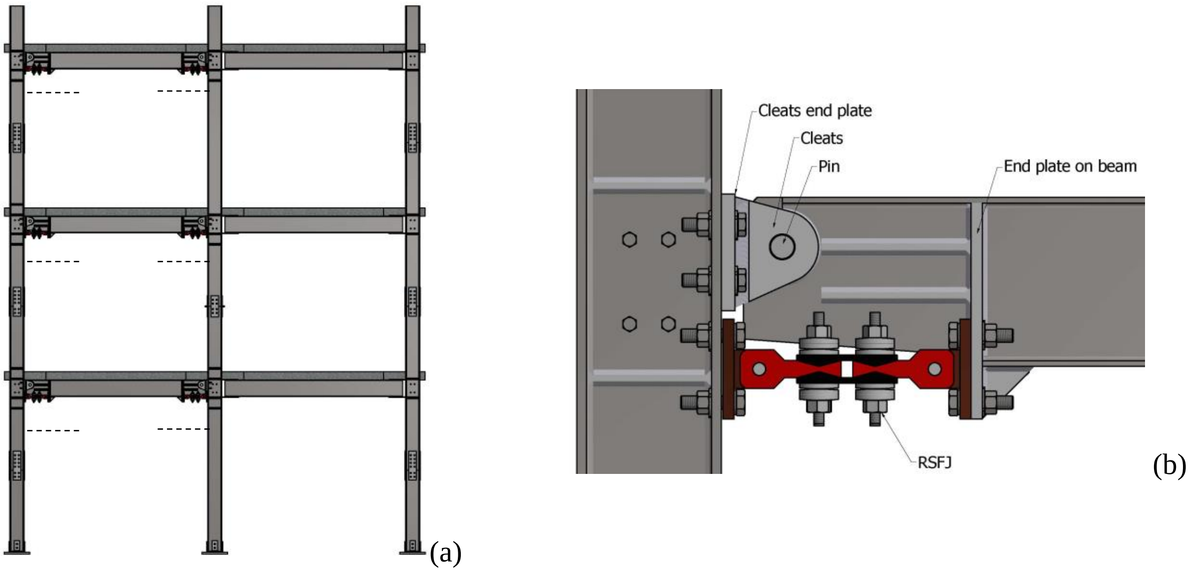


Figure 2: (a) Locations of the RSFJs shown by dash-line in the MRF concept and (b) connection details

Members design using equivalent static method (ESM)

Design of the beams have been completed using the equivalent static method with $\mu = 3$ and $S_p = 1$. The reason for taking *Sp* as unity is that there will be basic non-structural elements on the structure at the time of testing of this concept which might not be similar to a real building meaning that the response will not be decreased by the non-structural elements compared to a real building. Moreover, beams are checked against the over-strength capacity of the RSFJ.

Design of the columns has been completed by taking the lesser of the following actions:

i) Taking the upper limit actions assuming $\mu = 1.25$

ii) Taking the capacity design derived actions from the RSFJs over-strength capacity

In the numerical modelling for this part, elastic rotational links have been modelled at the beam to column connection to estimate more realistically the fundamental structural period. This has been undertaken using the Damper-Friction Spring link provided in SAP2000 [23] for the rotational degree of freedom. This elastic rotational stiffness is derived from the following equation:

Error! Objects cannot be created from editing field codes.

Where k_{init} is the initial axial stiffness of the RSFJ which is around 100 $^{kN}/_{mm}$ from testing done at the University of Auckland and L_e is the lever arm, distance between centre-lines of the top pin and RSFJs at the bottom as shown in Figure 3. Thus,

Error! Objects cannot be created from editing field codes.

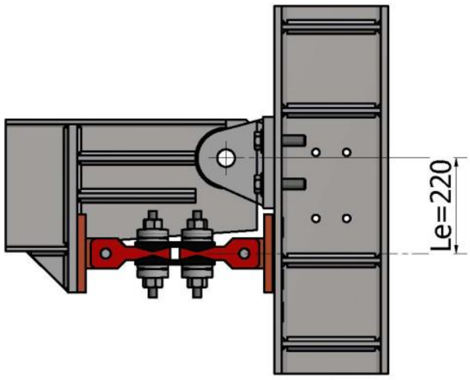


Figure 3: RSFJ-MRF connection detail showing Le parameter (mm)

Moreover, the column bases have been assigned elastic springs with the stiffness values corresponding to $0.1 EI/L$ and $1.67 EI/L$ for pinned and fixed conditions, respectively [24]; where E is the steel elastic modulus, I is the moment of the inertia of the column under the direction of interest, and L is the internal height of the column in the bottom story. The central column of the structure is a gravity column and therefore due to the detailing provided for this column, it is assumed pinned while all other columns are fixed. The floors have also been modelled using shell element with out-of-plane bending stiffness, to represent an elastic system. From this elastic model, the obtained modal periods are given in Table 2 and the Serviceability (SLS) and the Ultimate Limit State (ULS) base shears are calculated and reported in Table 3.

Table 2: Modal periods for the RSFJ MRF concept

Mode number	Mode period (s)
1	1.14
2	0.225
3	0.131

Table 3: SLS and ULS base shear from ESM analysis for the RSFJ MRF concept

Limit state	$R_{U/S}$	μ	S_p	Base shear (kN)
SLS	0.25	1	1	83
ULS	1	3	1	115

The designed section as a result of the ESM are given in Table 4.

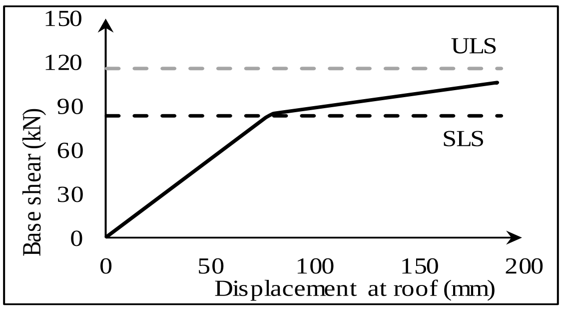
Table 4: Frame sections

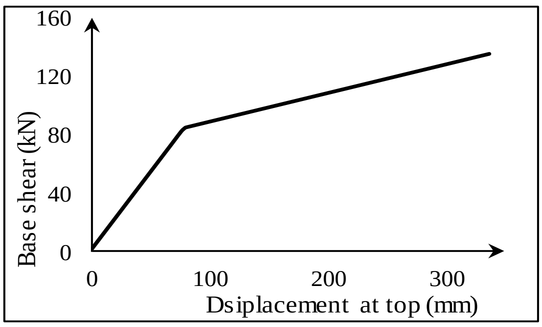
Member	Section
Lateral load resisting columns	254×254×89 UC
Gravity column	200×200×10 UC
Beam	305×165×40 SHS
Ring beam	HW 400×400

After the initial design, nonlinear pushover and time-history analyses are carried out to verify the performance of the structure more accurately and also to check the adequacy of the members and RSFJs using a procedure proposed by [25]. For this purpose, the non-linear flag-shape behaviour of the joints is modelled in SAP2000 [23] and the structure is pushed to the ULS and MCE drift levels.

Static pushover analysis to design the RSFJs

Joints are designed such that in the pushover analysis result, there should be no slippage in the joints and therefore the structure, before the SLS base shear from ESM and also the maximum base shear on the pushover curve should be less than the ULS base shear from ESM. As the purpose of this test is to see no damage in the structural system up to MCE, joints are designed to accommodate MCE rotation demand. The ULS drift limit is considered to be $2.5\%/k_{dm}$ where $k_{dm} = 1.2$ is the drift modification factor to account for the higher modes effects and the MCE level is 1.8 times of ULS drift. Figure 4 depicts the pushover response of the structure to ULS and MCE.



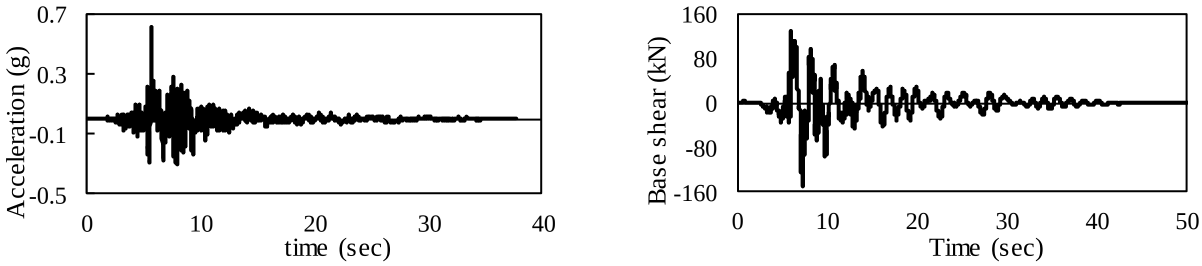


(a) (b)

Figure 4: RSFJ MRF structure response to pushover analysis under ULS and MCE

NLTHA

Due to the budget limitation to cover the considerable total number of tests related to the whole test alternatives, it was decided to select one earthquake record which matches perfectly the target spectrum over the interested period range. This record is the Imperial Valley, El Centro 1979, Array #8 station which then is scaled to the target spectrum using the NZS1170.5 [26]. Figure 5 includes this record scaled to the ULS and the corresponding base shear response of the RSFJ MRF structure.



(a) (b)

Figure 5: (a) Earthquake record scaled to ULS and (b) corresponding RSFJ MRF response

From the pushover response, the slipping point has occurred at the SLS base shear and the maximum base shear is less than the ULS base shear. Also, the maximum base shear from the NLTHA is less than the ULS base shear from pushover analysis.

RSFJ Tension-only braced configuration

In this concept, the RSFJ is combined with the DONOBrace which is a tension-only bracing system used in practice. This system is used in one bay of the longitudinal direction and at the two bottom stories. Figure 6 shows the details of the RSFJ tension-only brace in the structure. The design procedure implemented to design the RSFJ and the structural members is literally similar to the procedure mentioned in section 0 except for the column bases which are all assigned elastic springs for a pinned column base. The modal periods as well as the SLS and ULS base shear from ESM are given in *Table 5* and *Table 6*, respectively.

Table 5: Modal periods for the RSFJ MRF concept

Mode number	Mode period (s)
1	0.46
2	0.166
3	0.125

Table 6: SLS and ULS base shear from ESM analysis for the RSFJ MRF concept

Limit state	$R_{U/S}$	μ	S_p	Base shear (kN)
SLS	0.25	1	1	158
ULS	1	3	1	272

The pushover and NLTHA response of the structure are given in Figure 7.

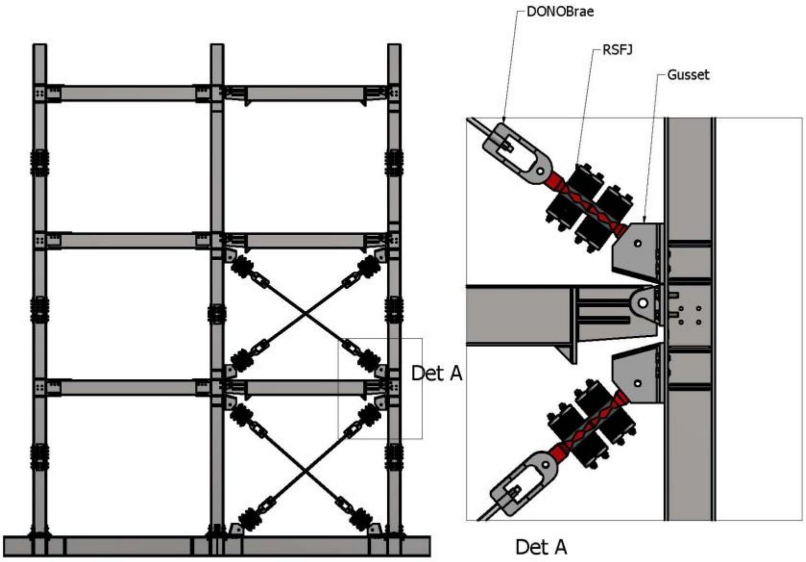


Figure 6: RSFJ tension-only brace combined with DONOBrace

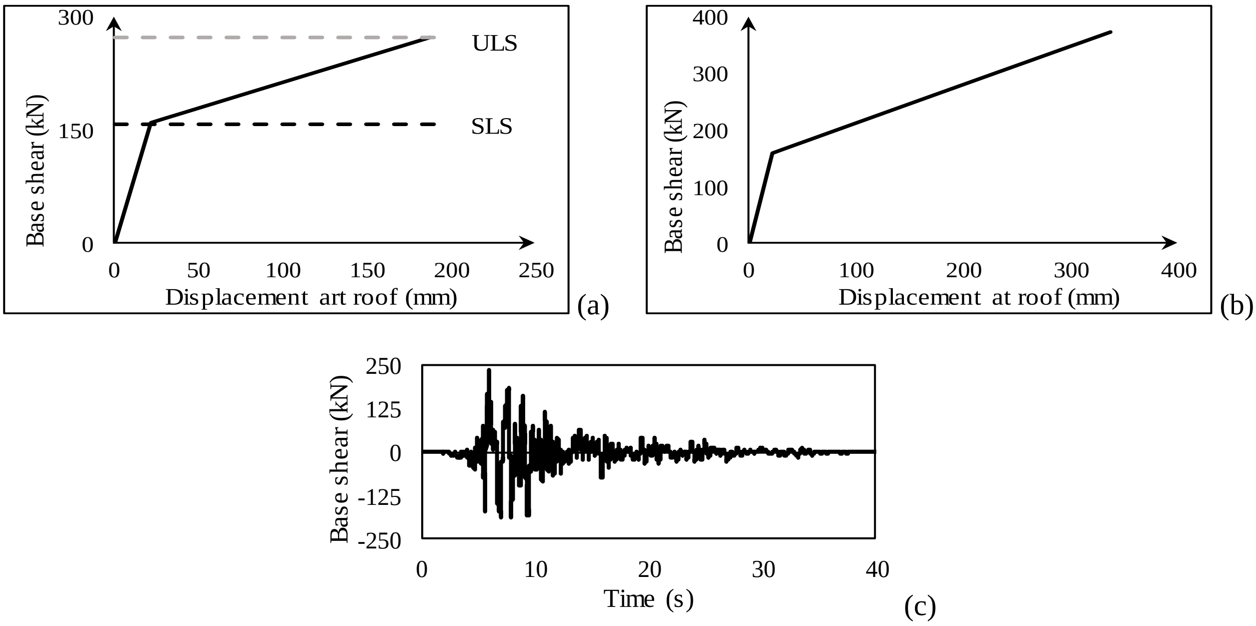


Figure 7: RSFJ tension-only braced structure response to (a) ULS pushover, (b) MCE pushover, and (c) ULS record

From the pushover response, the slipping point has occurred after the SLS base shear and the maximum base shear is around the ULS base shear. Also, the maximum base shear from the NLTHA is less than the ULS base shear from pushover analysis.

RSFJ tension-compression braced configuration

In this system, the RSFJ and the brace body undergo compression forces which involves the stability studies as well. In order to prevent brace buckling, an anti-buckling tube mechanism is used which is undertaken by a separate study [27]. This brace is also put at the locations similar to the tension-only braces. Figure 8 includes a view of the structure incorporating this concept. Likewise, the design procedure for this configuration is similar to the RSFJ tension-only brace configuration except that in the modeling, the braces works both in tension and compression. As a result of the ESM design, the brace section is 203×203×60 UC S355. The modal periods as well as SLS and ULS base shear are given in *Table 7* and *Table 8*, respectively.

Table 7: Modal periods for the RSFJ MRF concept

Mode number	**Mode period (s)**
1	0.48
2	0.17
3	0.154

Table 8: SLS and ULS base shear from ESM analysis for the RSFJ MRF concept

Limit state	$R_{U/S}$	μ	S_p	**Base shear (kN)**
SLS	0.25	1	1	156
ULS	1	3	1	264

Figure 9 demonstrates the ULS and MCE pushover response of the structure as well as the NLTHA response to the ULS event.

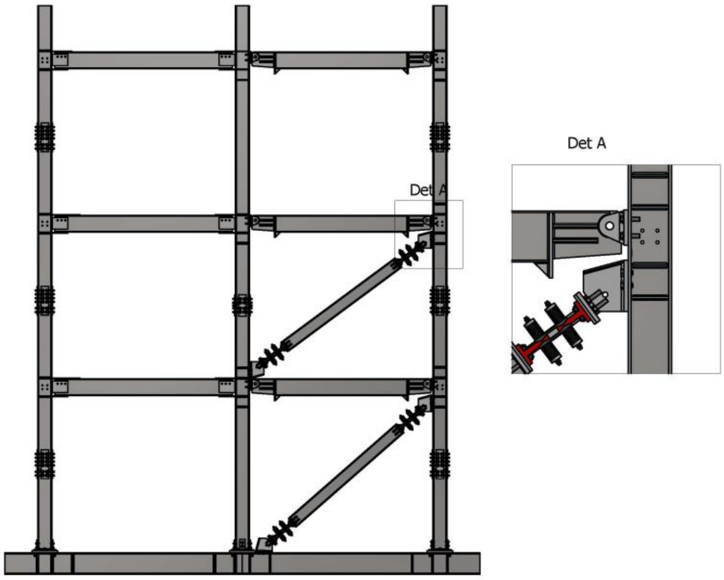


Figure 8: RSFJ tension-compression braced structure

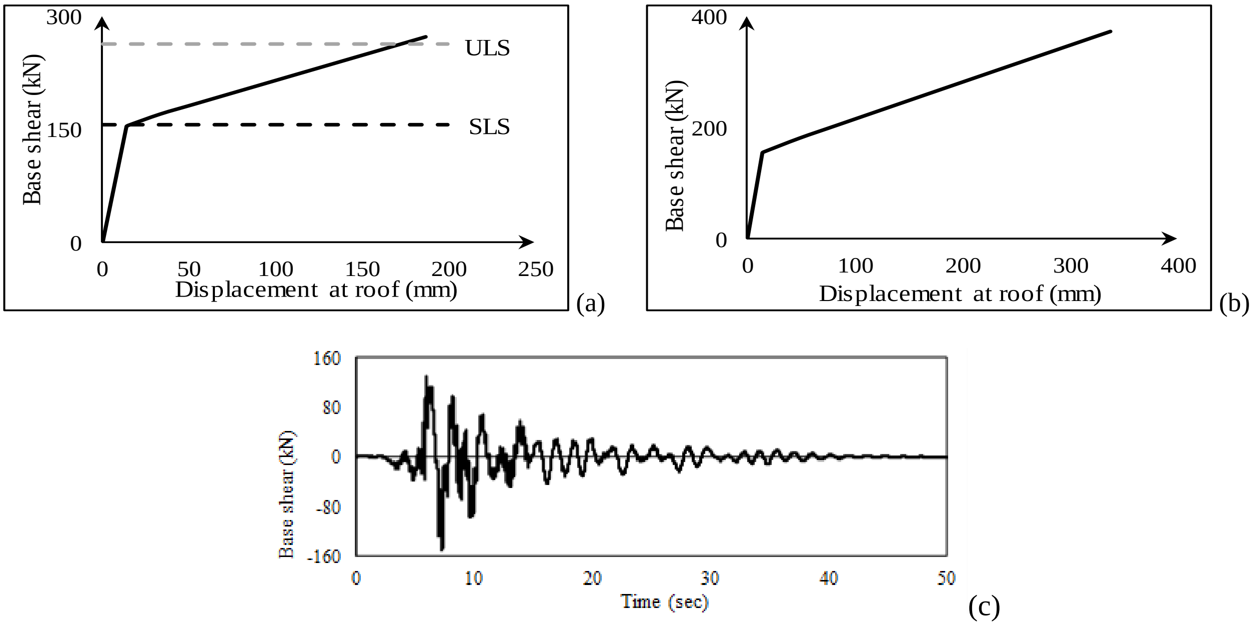


Figure 9: RSFJ tension-compression braced structure response to (a) ULS pushover, (b) MCE pushover, and (c) ULS record

From the pushover response, the slipping point has occurred at the SLS base shear and the maximum base shear is around the ULS base shear. Also, the maximum base shear from the NLTHA is less than the ULS base shear from pushover analysis.

Conclusions

This paper presented the design and numerical analyses related to the shaking table testing of a full-scale three-dimensional steel structure in which three RSFJ structural applications are considered separately. The applications studied are tension-only brace, tension-compression brace, and MRF. Adopting a robust design procedure including ESM for initial design of members and then conducting pushover and NLTHA, the adequacy of members and RSFJs up to MCE was checked. Having designed a resilient structure using the RSFJs, the likelihood of any need for repair and replacing structural components is considerably declined.

Acknowledgement

This work described is part of a joint NZ-China research program with ILEE, Tongji University, Shanghai, China and directly with Tongji University, Shanghai, China. Direct NZ funding is kindly provided by the Ministry of Business, Innovation, and Education (MBIE), Building Research Association of NZ (BRANZ) under the Building Research Levy, the Earthquake Commission (EQC), the HERA Foundation (a charitable trust associated with HERA), QuakeCentre, the Tertiary Education Commission funded QuakeCoRE (the NZ ILEE partner through whom the NZ funding is also coordinated), and the University of Auckland (UA). Donations of materials is kindly provided by Comflor, Hilti Corporation, Forman Building Systems, Gripple, Lanyon & LeCompte Construction Ltd., and Alutech Doors & Windows Ltd. Expertise has been generously provided by a number of NZ industry representatives. The authors gratefully acknowledge this support. Opinions expressed are those of the authors alone. The QuakeCoRE paper number is 0549.

Bibliography

[1] H. Wang, X. Nie, and P. Pan, "Development of a self-centering buckling restrained brace using cross-anchored pre-stressed steel strands," *J. Constr. Steel Res.*, vol. 138, pp. 621–632, 2017.

[2] J. M. Ricles, R. Sause, S. W. Peng, and L. W. Lu, "Experimental evaluation of earthquake resistant posttensioned steel connections," *J. Struct. Eng.*, vol. 128, no. 7, pp. 850–859, 2002.

[3] K. Tsai, C. Chou, C. Lin, P. Chen, and S. Jhang, "Seismic self-centering steel beam-to-column moment connections using bolted friction devices," *Earthq. Eng. Struct. Dyn.*, vol. 37, no. 4, pp. 627–645, 2008.

[4] C. Clifton, M. Bruneau, G. MacRae, R. Leon, and A. Fussell, "Steel building damage from the Christchurch earthquake series of 2010/2011," *SESOC J.*, vol. 24, no. 2, p. 27, 2011.

[5] H. Ma and M. C. H. Yam, "Modelling of a self-centring damper and its application in structural control," *J. Constr. Steel Res.*, vol. 67, no. 4, pp. 656–666, 2011.

[6] C. Chou, J. Chen, Y. Chen, and K. Tsai, "Evaluating performance of post-tensioned steel connections with strands and reduced flange plates," *Earthq. Eng. Struct. Dyn.*, vol. 35, no. 9, pp. 1167–1185, 2006.

[7] A. Palermo, S. Pampanin, and G. M. Calvi, "Concept and development of hybrid solutions for seismic resistant bridge systems," *J. Earthq. Eng.*, vol. 9, no. 06, pp. 899–921, 2005.

[8] A. A. Rad, G. A. MacRae, N. Hazaveh K., and T. M. Quincy, "Shake Table Testing of a Low Damage Steel Building with Asymmetric Friction Connections (AFC)," *Key Eng. Mater.*, vol. 763, 2018.

[9] C. Qiu and S. Zhu, "Shake table test and numerical study of self-centering steel frame with SMA braces," *Earthq. Eng. Struct. Dyn.*, vol. 46, no. 1, pp. 117–137, 2017.

[10] J. Erochko, C. Christopoulos, R. Tremblay, and H. Kim, "Shake table testing and numerical simulation of a self-centering energy dissipative braced frame," *Earthq. Eng. Struct. Dyn.*, vol. 42, no. 11, pp. 1617–1635, 2013.

[11] 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.

[12] P. Zarnani and P. Quenneville, "A Resilient Slip Friction Joint," WO2016185432A1, 2015.

[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] H. Bagheri, A. Hashemi, S. M. M. Yousef-beik, P. Zarnani, and P. Quenneville, "Experimental test of a new self-centring tension-only brace using the Resilient Slip Friction Joint," in *Pacific Conference on Earthquake Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE) Conference*, 2019.

[15] H. Bagheri, A. Hashemi, F. Darani, P. Zarnani, and P. Quenneville, "A New Self-Centering Tension-Only Brace for Seismic Proofing of New and Existing Structures," 2018.

[16] F. M. Darani, P. Zarnani, A. Hashemi, H. Bagheri, P. Quenneville, and E. Haemmerle, "Self-centring pre-cast concrete shear walls with resilient slip friction joint, a new damage aviodance structural system," in *The Concrete NZ Conference*, 2018.

[17] S. M. M. Yousef-beik, P. Zarnani, F. Mohammadi, A. H. Darani, and P. Quenneville, "New Seismic Damage Avoidant Timber Brace Using Innovative Resilient Slip Friction Joints For Multi-Story Applications," *World Conf. Timber Eng.*, 2018.

[18] S. M. Shabankareh, P. Zarnani, A. Hashemi, and P. Quenneville, "A novel connection system for seismic damage avoidance design of moment resisting frames," in *Pacific Conference on Earthquke Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*, 2019.

[19] S. Veismoradi, P. Zarnani, and P. Quenneville, "Development of self-centring Rotational Slip Friction Joint: a novel damage-free damper with large deflections," in *Pacific Conference on Earthquke Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*, 2019.

[20] K. Sahami, S. Veismoradi, P. Zarnani, and P. Quenneville, "Seismic Performance of Rocking Concrete Shear Walls with Innovative Rotational Resilient Slip Friction Joints," in *Pacific Conference on Earthquke Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*, 2019.

[21] A. Hashemi, G. C. Clifton, H. Bagheri, P. Zarnani, and P. Quenneville, "Proposed design procedure for damage-avoidance braced frames with braces effective in tension only," in *Pacific Conference on Earthquke Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*, 2019.

[22] A. Hashemi, H. Bagheri, S. M. Beik, P. Zarnani, and P. Quenneville, "The Equivalent Ductility approach for designing the structures using Resilient Slip Friction Joints (RSFJs)," in *Pacific Conference on Earthquke Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*, 2019.

[23] CSi, "SAP2000, Structural Software for Analysis and Design." 2019.

[24] Z. Yan *et al.*, "Shaking table test of a near full scale low damage structural steel building: structural aspects," 2019.

[25] 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.

[26] NZS1170.5, "NZS 1170.5: 2004 Structural Design Actions Part 5: Earthquake actions–New Zealand," 2004.

[27] S. M. M. Yousef-beik, S. Veismoradi, P. Zarnani, and P. Quenneville, "Full Scale Quasi-Static Testing of a New Self-Centering Damage-Avoidant Timber Brace," in *17th World Conference on Earthquake Engineering*, 2020.

