Full-scale shaking table testing of a low-damage steel structure using Resilient Slip Friction Joint

H. Bagheri, A. Hashemi, P. Quenneville, Z. Yan & G.C. Clifton
The University Of Auckland, Auckland.

P. Zarnani
Auckland University of Technology, Auckland.

G.A. MacRae
Tongji University, China & University of Canterbury, Christchurch.

ABSTRACT

The objective of this study is to give an overview of the design and numerical analyses related to a full-scale steel structure shaking table test that includes some structural applications of Resilient Slip Friction Joint (RSFJ) as low-damage systems. 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. A full-scale three-dimensional three-story steel structure was designed using the equivalent static method. The structure was 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 were designed in different applications using nonlinear push-over analysis including joints nonlinearity. Then, nonlinear time-history analysis (NLTHA) was undertaken to check the members and the RSFJs adequacy. One record was selected which acceptably matched the site target spectrum over the period range of interest and was 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 was proposed with no need to replace any structural component which in turn can meet immediate occupancy requirements.

Keywords: *Seismic, full-scale testing, shaking table test, RSFJ, self-centring*

1 INTRODUCTION

The objective of this research is to present an overview of 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 were 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 (Wang, Nie, and Pan 2017). In the technical literature, different residual drift limits have been suggested for different levels of performance. Based on the research conducted by (Ricles et al. 2002 and Tsai et al. 2008), if the residual drift is greater than 0.5%, the structure is potentially demolished taking into account human-feeling and safety considerations. (Clifton et al. 2011) 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 (Ma and Yam 2011), beam-to-column-connections (Chou et al. 2006; Janke et al. 2005; Ricles et al. 2002; and Tsai et al. 2008), steel MRFs (Tsai et al. 2008), and bridges (Palermo, Pampanin, and Calvi 2005). Moreover, newly developed smart materials such as shape memory alloy (SMA) are alternative solutions for providing self-centring capabilities to structures. (Palermo et al. 2005) carried out a three-dimensional, three-story, 2/3rd scaled Pres-Lam frame building. The Pre-Lam is a recent technology for multi-story timber buildings that uses pre-stressing steel tendons or bars for connecting prefabricated laminated timber members. The tests results were compared with numerical predictions of non-linear analysis; this comparison proved the accuracy of the numerical models to predict the dynamic response and the efficiency of the system. (Rad et al. 2018) 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%. (Qiu and Zhu 2017) 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%. (Erochko et al. 2013) 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 (Christopoulos et al. 2008) 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) was recently invented by Zarnani and Quenneville (Zarnani and Quenneville 2015) 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 were developed (Hashemi et al. 2016). Also, the joint was tested in different structural applications to bring resiliency to their seismic performance including steel tension-only brace (Bagheri et al. 2020) which can be used for retrofitting applications as well (Bagheri et al. 2018), rocking Cross Laminated Timber (CLT) shear wall (Hashemi et al. 2016), pre-cast concrete shear wall (M. Darani et al. 2018), tension-compression brace including the stability studies of the joint and brace body (Yousef-beik, Veismoradi, Zarnani, and Quenneville 2020). The rotational version of the RSFJ in order to enhance the displacement capacity was developed by (Veismoradi et al. 2019) which has also been studied into rocking concrete shear walls (Sahami et al. 2019). (Hashemi et al. 2020) gave a proposed design procedure for design of tension-only RSFJ bracing system and (Hashemi et al. 2020) presented 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.

2 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 was 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 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. Figure 1 includes the plan and side views of the structure considered including dimensions. The structure includes column splices at mid-height of columns in each story of the corner columns, as shown in Figure 1(c), to make possible the rocking action happening in the transverse direction, gridlines 1 and 3 in Figure 1 (a). In addition, a splice has been placed at the mid-height of the other columns of the structure to facilitate the erection process.

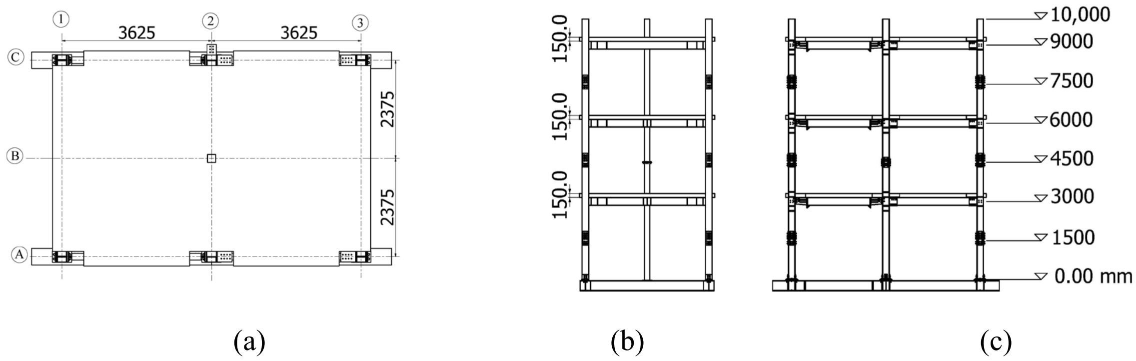

Figure 1: (a) Plan, (b) transverse, and (c) longitudinal views of the test structure (mm)

The composite flooring system with trapezoidal steel deck and concrete on top, was considered as the permanent load on the structure. In order to simulate the imposed load, additional mass blocks were used for different stories which imposed 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 was 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 was 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 are given in which it is aimed to have a robust building up to MCE.

3 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 was used in the longitudinal direction of the test structure and only in one bay while the other bay will had simple connections. The RSFJs were 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.

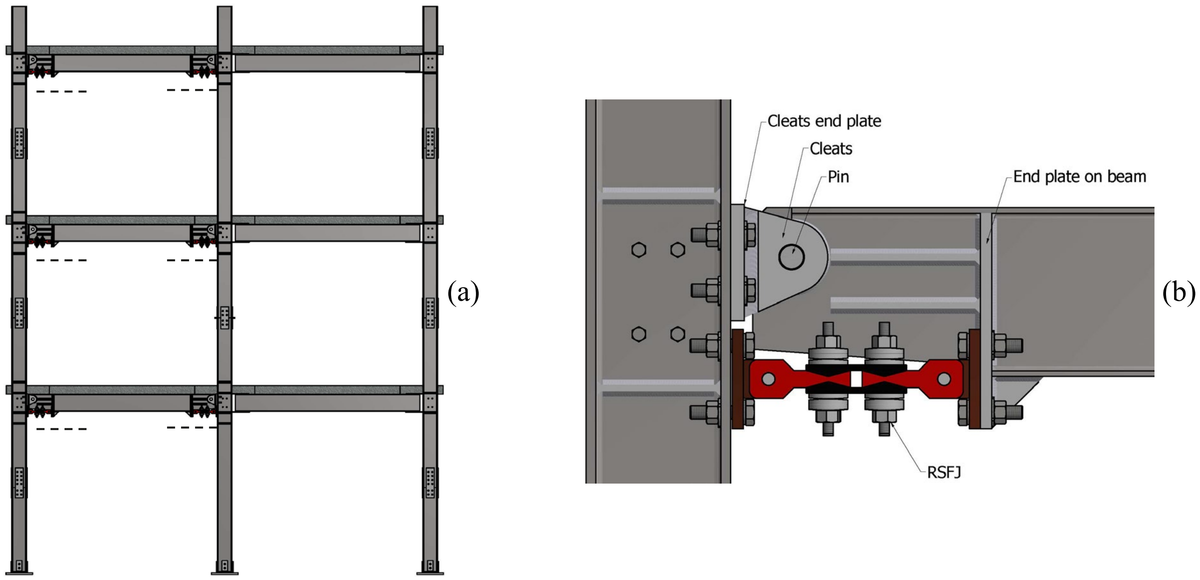

Figure 2: (a) Locations of the RSFJs shown by dash-line in the MRF concept and (b) connection details

3.1 Members design using equivalent static method (ESM)

Design of the beams were completed using the equivalent static method with $\mu = 3$ and $S_p = 1$. The reason for taking S_p 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 where the strength/stiffness is increased by the non-structural elements. Moreover, beams were checked against the over-strength capacity of the RSFJ.

Design of the columns were completed by taking the lesser of the following actions:

1. Taking the upper limit actions assuming $\mu = 1.25$
2. Taking the capacity design derived actions from the RSFJs over-strength capacity

In the numerical modelling for this part, elastic rotational links were modelled at the beam to column connection to estimate more realistically the fundamental structural period. This was undertaken using the Damper-Friction Spring link provided in SAP2000 (CSi 2019) for the rotational degree of freedom. Moreover, the column bases were assigned elastic springs with the stiffness values corresponding to $0.1\,{EI}/{L}$ and $1.67\,{EI}/{L}$ for pinned and fixed conditions respectively (Yan et al. 2019); 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 was a gravity column and therefore due to the detailing provided for this column, it was assumed pinned while all other columns were fixed. The floors were modelled using shell element with out-of-plane bending stiffness, to represent an elastic system. From this elastic model, the Serviceability (SLS) and the Ultimate Limit State (ULS) base shears were calculated and reported in Table 3.

Table 2: SLS and ULS base shear from ESM analysis for 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

Table 3: 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

The designed section as a result of the ESM are given in Table 4. After the initial design, nonlinear pushover and time-history analyses were 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 (Hashemi et al. 2018).

For this purpose, the non-linear flag-shape behaviour of the joints was modelled in SAP2000 (CSi 2019) and the structure was pushed to the ULS and MCE drift levels.

3.2 Static pushover analysis to design the RSFJs

Joints were 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 was to see no damage in the structural system up to MCE, joints were designed to accommodate MCE rotation demand. The ULS drift limit was 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 was considered 1.8 times of ULS drift. Figure 3 depicts the pushover response of the structure to ULS and MCE. As can be observed in Figure 3, the structure has no slip before the SLS base shear and also the ULS base shear from ESM is within 5% of the maximum force on the pushover curve.

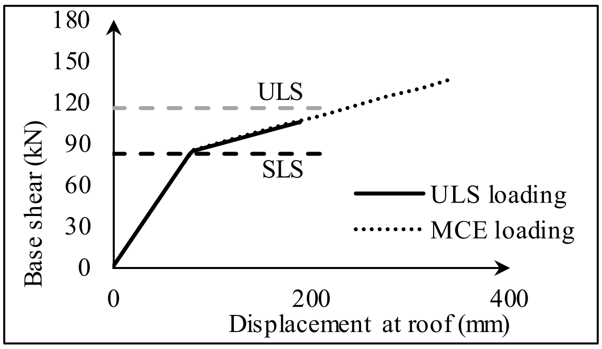

Figure 3: RSFJ MRF structure response to pushover analysis under ULS and MCE

3.3 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 1940, Array #9 station which then is scaled to the target spectrum using the NZS1170.5 (NZS1170.5 2004). Figure 4 includes this record scaled to the ULS and the corresponding base shear response of the RSFJ MRF structure. From NLTHA, joints as well as members adequacy was further checked.

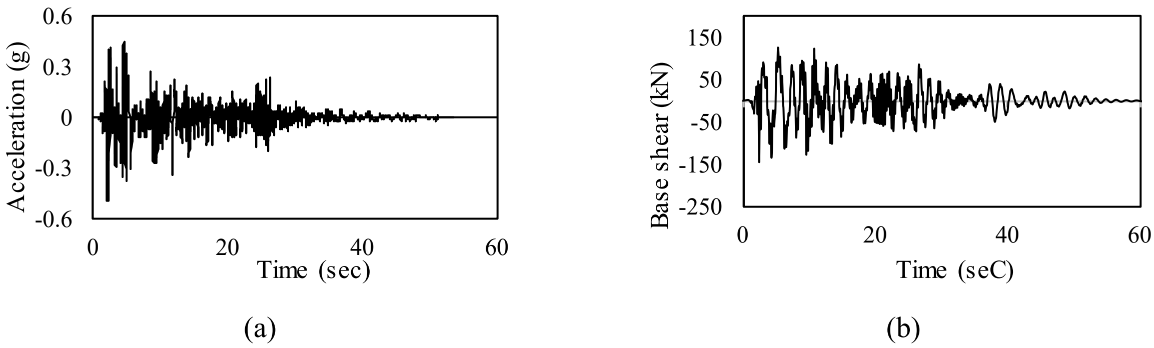

Figure 4: (a) Earthquake record scaled to ULS and (b) corresponding RSFJ MRF response

4 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 was used in one bay of the longitudinal direction and at the two bottom stories. Figure 5 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 3 except for the column bases which were all assigned elastic springs for a pinned column base. Thus, only the pushover and NLTHA response of the structure are given in Figure 6. The SLS and ULS base shear from ESM were 158kN and 272kN, respectively. As can be observed, the structure had no slip before the SLS base shear and also the ULS base shear from ESM was within 5% of the maximum force on the pushover curve. Moreover, maximum base shear of NLTHA was less than the base shear obtained from ESM.

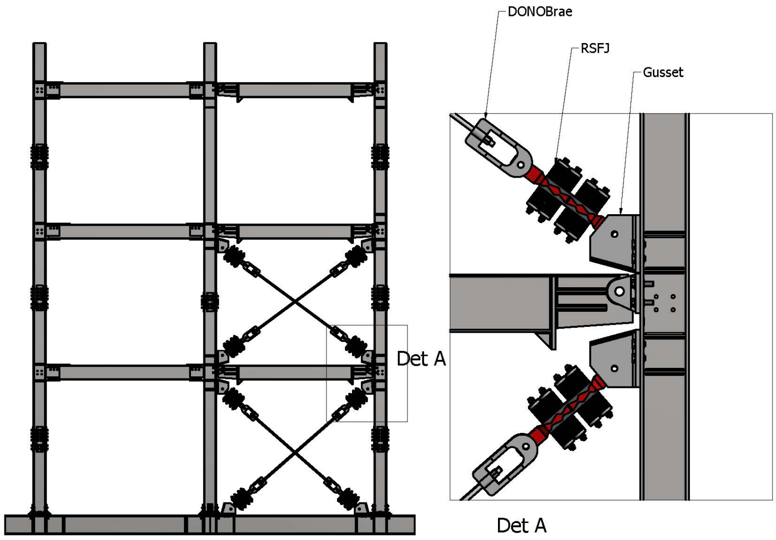

Figure 5: RSFJ tension-only brace combined with DONOBrace

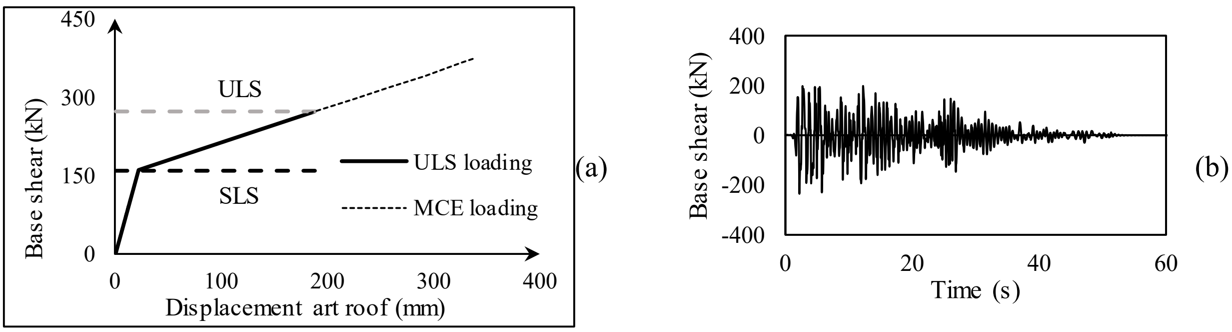

Figure 6: RSFJ tension-only braced structure response to (a) pushover loading and (b) ULS-scaled record

5 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 was used. The focus of this paper is not to go through the stability studies of the brace components which were undertaken by a separate research (Yousef-beik et al. 2020). This brace was also put at the locations like the tension-only braces. Figure 7 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 was 203×203×60

UC S355. The SLS and ULS base shear were 156kN and 264kN, respectively. Figure 8 demonstrates the ULS and MCE pushover response of the structure as well as the NLTHA response to the ULS event. As can be observed, the structure has no slip before the SLS base shear and also the ULS base shear from ESM is within 5% of the maximum force on the pushover curve. Moreover, maximum base shear of NLTHA was less than the base shear obtained from ESM.

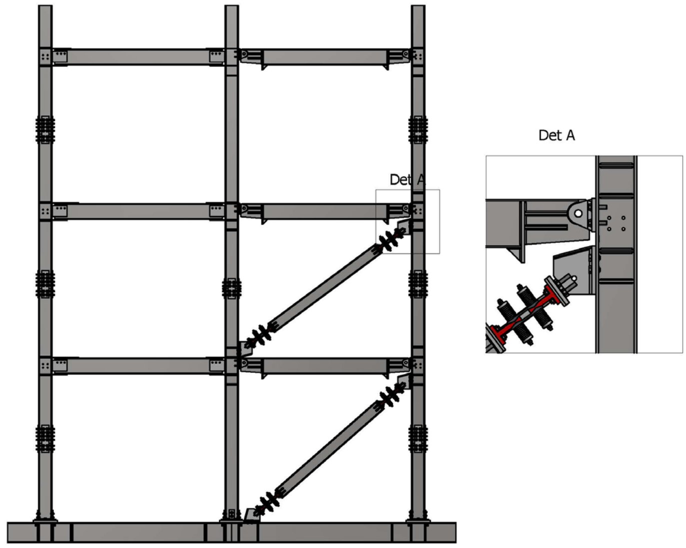

Figure 7: RSFJ tension-compression braced structure

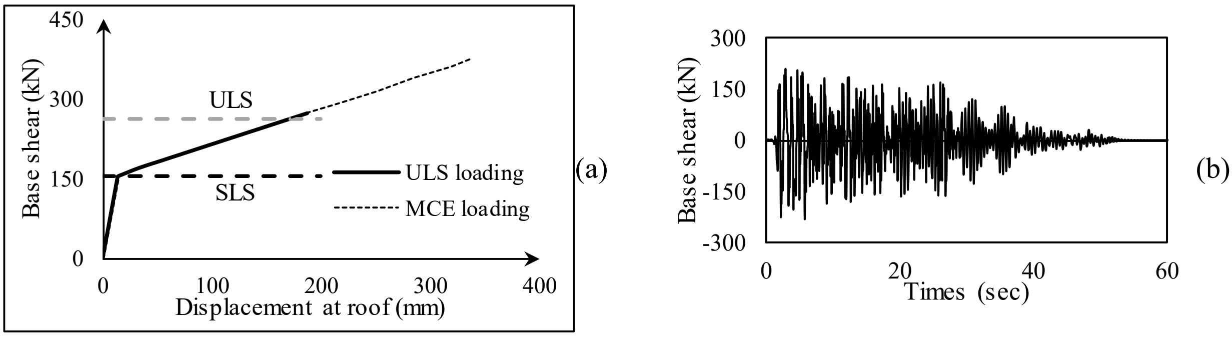

Figure 8: RSFJ tension-compression braced structure response to (a) pushover loading and (b) ULS-scaled record

6 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 were considered separately. The applications studied were tension-only brace, tension-compression brace, and MRF. Adopting a robust design procedure, including ESM for the initial design of members and then conducting pushover and NLTHA, the adequacy of members and RSFJs up to MCE was checked; the columns were fully elastic which confirms the assumed design ductility of 1.25. Having designed such a resilient structure using the RSFJs, the likelihood of any requirement for repairing and replacing the structural components is considerably declined since the expected residual drift is zero.

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 Employment (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 0519.

REFERENCES

Bagheri, Hamed, Ashkan Hashemi, Farhad Darani, Pouyan Zarnani, and Pierre Quenneville. 2018. "A New Self-Centering Tension-Only Brace for Seismic Proofing of New and Existing Structures." Perth, W.A.: Australian Earthquake Engineering Society (AEES).

Bagheri, Hamed, Ashkan Hashemi, Mohammd Mahdi Yousef-beik, Pouyan Zarnani, and Pierre Quenneville. Forthcoming. "A New Self-Centering Tension-Only Brace Using Resilient Slip Friction Joint: Experimental Tests and Numerical Analysis." *ASCE, Journal of Structural Engineering*. 10.1061/(ASCE)ST.1943-541X.0002789.

Chou, Chung-Che, Jun-Hen Chen, Yu-Chih Chen, and Keh-Chyuan Tsai. 2006. "Evaluating Performance of Post-tensioned Steel Connections with Strands and Reduced Flange Plates." *Earthquake Engineering & Structural Dynamics* 35(9):1167–85.

Christopoulos, C., R. Tremblay, H. J. Kim, and M. Lacerte. 2008. "Self-Centering Energy Dissipative Bracing System for the Seismic Resistance of Structures: Development and Validation." *Journal of Structural Engineering* 134(1):96–107.

Clifton, Charles, Michael Bruneau, Greg MacRae, Roberto Leon, and Alistair Fussell. 2011. "Steel Building Damage from the Christchurch Earthquake Series of 2010/2011." *SESOC Journal* 24(2):27.

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

Erochko, Jeffrey, Constantin Christopoulos, Robert Tremblay, and Hyung-Joon Kim. 2013. "Shake Table Testing and Numerical Simulation of a Self-centering Energy Dissipative Braced Frame." *Earthquake Engineering & Structural Dynamics* 42(11):1617–35.

Hashemi, A., H. Bagheri, F. M. Darani, S. M. M. Yousef-Beik, P. Zarnani, and P. Quenneville. 2018. "An Example Procedure for Preliminary Sizing of Resilient Slip Friction Joints (RSFJS) in Seismic Resistant Structures." *SESOC Journal* 31(2):44.

Hashemi, Ashkan, Hamed Bagheri, Seyed Mohamad Mahdi Yousef-beik, Farhad Mohammadi Darani, Pouyan Zarnani, and Pierre Quenneville. Forthcoming. "Enhanced Seismic Performance of Timber Structures Using Resilient Connections: Full-Scale Testing and Design Procedure." *ASCE, Journal of Structural Engineering*.10.1061/(ASCE)ST.1943-541X.0002749.

Hashemi, Ashkan, George Charles Clifton, Hamed Bagheri, Pouyan Zarnani, and Pierre Quenneville. 2020. "Proposed Design Procedure for Steel Self-Centring Tension-Only Braces with Resilient Connections." Pp. 147–56 in *Structures*. Vol. 25. Elsevier.

Hashemi, Ashkan, P. Zarnani, A. Valadbeigi, R. Masoudnia, and Pierre Quenneville. 2016. "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*.

Janke, L., C. Czaderski, M. Motavalli, and J. Ruth. 2005. "Applications of Shape Memory Alloys in Civil Engineering Structures—Overview, Limits and New Ideas." *Materials and Structures* 38(5):578–92.

M. Darani, Farhad, Pouyan Zarnani, Ashkan Hashemi, Hamed Bagheri, Pierre Quenneville, and Enrico Haemmerle. 2018. "Self-Centring Pre-Cast Concrete Shear Walls with Resilient Slip Friction Joint, a New Damage Aviodance Structural System." in *The Concrete NZ Conference*. Claudelands, Hamilton.

Ma, Hongwei and Michael C. H. Yam. 2011. “Modelling of a Self-Centring Damper and Its Application in Structural Control.” *Journal of Constructional Steel Research* 67(4):656–66.

NZS1170.5. 2004. *NZS 1170.5: 2004 Structural Design Actions Part 5: Earthquake Actions–New Zealand*.

Palermo, Alessandro, STEFANO Pampanin, and GIAN MICHELE Calvi. 2005. “Concept and Development of Hybrid Solutions for Seismic Resistant Bridge Systems.” *Journal of Earthquake Engineering* 9(06):899–921.

Qiu, Canxing and Songye Zhu. 2017. “Shake Table Test and Numerical Study of Self-centering Steel Frame with SMA Braces.” *Earthquake Engineering & Structural Dynamics* 46(1):117–37.

Rad, Ali A., Gregory A. MacRae, Nikoo Hazaveh K., and T. Ma Quincy. 2018. “Shake Table Testing of a Low Damage Steel Building with Asymmetric Friction Connections (AFC).” *Key Engineering Materials* 763.

Ricles, J. M., R. Sause, S. W. Peng, and L. W. Lu. 2002. “Experimental Evaluation of Earthquake Resistant Posttensioned Steel Connections.” *Journal of Structural Engineering* 128(7):850–59.

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

Tsai, Keh-Chyuan, Chung-Che Chou, Chi-Lon Lin, Pei-Ching Chen, and Sheng-Jhih Jhang. 2008. “Seismic Self-centering Steel Beam-to-column Moment Connections Using Bolted Friction Devices.” *Earthquake Engineering & Structural Dynamics* 37(4):627–45.

Veismoradi, S., P. Zarnani, and P. Quenneville. 2019. “Development of Self-Centring Rotational Slip Friction Joint: A Novel Damage-Free Damper with Large Deflections.” in *Pacific Conference on Earthquake Engineering (PCEE) and New Zealand Society for Earthquake Engineering (NZSEE), Auckland, New Zealand*. Auckland, New Zealand.

Wang, Haishen, Xin Nie, and Peng Pan. 2017. “Development of a Self-Centering Buckling Restrained Brace Using Cross-Anchored Pre-Stressed Steel Strands.” *Journal of Constructional Steel Research* 138:621–32.

Yan, Zhenduo, Hamed Bagheri, Charles Clifton, Pierre Quenneville, Shahab Ramhormozian, Gregory MacRae, Rajesh Dhakal, X. Zhao, L. Jia, and P. Xiang. 2019. “Shaking Table Test of a near Full Scale Low Damage Structural Steel Building: Structural Aspects.” Auckland.

Yousef-beik, Seyed Mohamad Mahdi, Sajad Veismoradi, Pouyan Zarnani, Ashkan Hashemi, and Pierre Quenneville. 2020. “Self-Centring Bracing System: Avoidance of Elastic Buckling For Braces with One Intermediate Damper.” in *NZSEE Annual Conference*. Wellington.

Yousef-beik, Seyed Mohamad Mahdi, Sajad Veismoradi, Pouyan Zarnani, and Pierre Quenneville. 2020. “A New Self-Centering Brace with Zero Secondary Stiffness Using Elastic Buckling.” *Journal of Constructional Steel Research* 169:106035.

Zarnani, Pouyan and Pierre Quenneville. 2015. “A Resilient Slip Friction Joint.” Patent No. WO2016185432A1, NZ IP Office.