Shake-table testing of the resilient slip friction joints

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ABSTRACT

A consortium of university researchers (The University of Auckland, Auckland University of Technology and Canterbury University) from New Zealand and Tongji University have undertaken shake-table tests of various friction damping devices. This testing program is under the banner of the ROBUST testing and is taking place at the ILEE Testing Laboratory at Tongji University in China. Essentially, a full-scale 3 storey steel structure serves as the framework where the seismic damping devices are attached and tested. As part of this testing, three different configurations of the resilient slip friction joints (RSFJ) developed at the University of Auckland are tested to demonstrate the behaviour of the structure under shake-table seismic excitations. The three RSFJ configurations tested are: tension-compression braces, tension-only cross-bracing and the moment resisting frame configuration. The shake-table tests observations and results are discussed and presented along with the conclusions.

1 INTRODUCTION

Observations from recent major earthquakes worldwide have demonstrated that while modern seismic designs can ensure life safety with soundly designed and constructed structures, the structures may be damaged during an earthquake, requiring costly repairs and replacements, often rendering the structures non-operational and left to be demolished. As a result of these damage observations, efforts have been made to reduce structural damage during major seismic events through the implementation of energy dissipation systems and or low-damage structural systems. It is possible to achieve low-damage performance of structures by maintaining the structure's elastic capacity (via capacity protection - overstrength) and incorporating energy dissipators such as friction or viscous dampers, or by utilizing a base isolation technique. There has been extensive development of friction connections starting with (Pall et al. 1980) and various symmetrical and asymmetrical friction connections have been developed to suit a variety of applications and achieve the optimal energy dissipation and application. Friction solutions reduce structural damage by providing very efficient and noticeable damping, however, the majority may suffer residual displacement following an earthquake, requiring adjustments to the connections and or the structure as a whole. Residual drift is an important indicator of a structure's repairability and useability following an earthquake. A great deal of effort has been expended by researchers and engineers to resolve the residual drift issue and provide a system that provides self-centring and damping while providing a resilient and low-damage solution. The Resilient Slip Friction Joint (RSFJ) was developed at the University of Auckland (Zarnani and Quennevill e 2015) in response to the 2010-2011 Canterbury earthquake series, resulted in catastrophic damage and trauma for the communities. In addition, the RSFJ was designed to provide a complete solution that addressed all of the above points while also being flexible and able to be implemented in a variety of construction types and configurations. Through the past studies, the governing equations of the joint have been developed (Hashemi et al. 2016) and the joint has been tested in different structural applications as a means of improving seismic performance, including steel tension-only brace (Bagheri et al. 2020), rocking Cross Laminated Timber (CLT) shear wall (Hashemi et al. 2018), pre-cast concrete shear wall (Mohammadi Darani et al. 2018), timber brace including the stability studies of the joint and brace body (Yousef-beik et al. 2021) amongst others. RSFJ studies conducted in the past were primarily experimental and numerical studies conducted at the component or system level, and they were successful in confirming and predicting the hysteresis response of the joint. However, to develop further certainty in the structural applications of the RSFJ, it is imperative to conduct dynamic shake table tests in order to assess their performance at the structural level.

1.1 Resilient slip friction joint (RSFJ)

The Resilient Slip Friction Joint (RSFJ) provides energy dissipation, self-centering, in both tension and compression, without causing any component to yield. There is also an additional safety mechanism in the form of a secondary fuse that ensures that the structure will not collapse during an earthquake event beyond the design level (Valadbeigi et al. 2018). The RSFJ consists of grooved cap plates, grooved middle plates, disk springs and pre-stressed bolts or rods (Figure 1). The RSFJ is activated when the force demand exceeds the slip force (resisting friction force between clamped plates), dissipating energy through friction as the cap plates slide onto the grooved middle plates. By compressing the grooved plates together, pre-stressed bolts and disc springs increase the friction force required to slide the plates and provide self-centering by forcing the grooved cap plates to return to their original position. Variation in geometry and other parameters enables the RSFJ to conform to almost any force and displacement required by the design. The RSFJ delivers repeatable and multi-cycle energy dissipation without damage or yield to elements and ensures continuous protection through earthquakes and aftershocks.

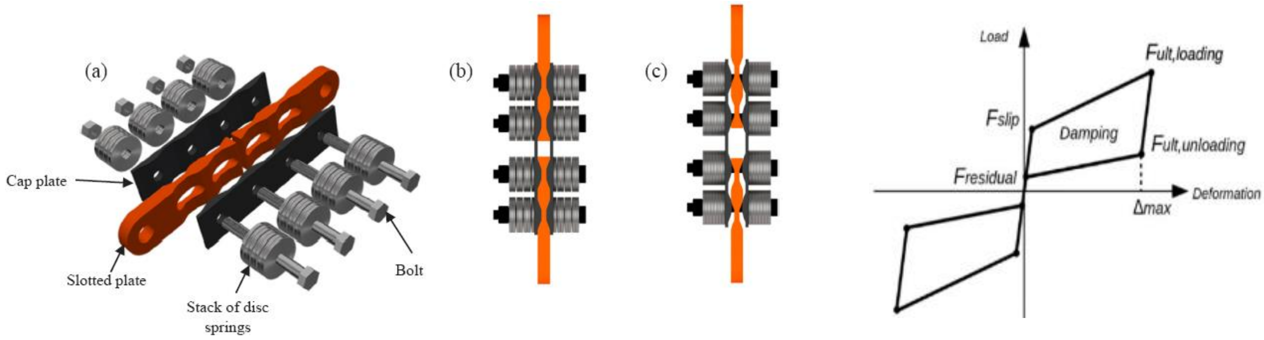

Figure 1: Resilient Slip Friction Joint (RSFJ): (a) joint parts assembly (b) joint at rest (c) joint at maximum opening (d) joint idealized flag shaped hysteresis.

1.2 Test structure description

The test structure has three stories with an inter-story height of 3m and total planar dimensions of 7.25 by 4.75m with two bays in the long direction and one bay in the shorter direction. Figure 2 illustrates the plan and side views of the structure with dimensions. A detailed description of the structure, RSFJ configurations and its detailed design can be found in (Bagheri 2022).

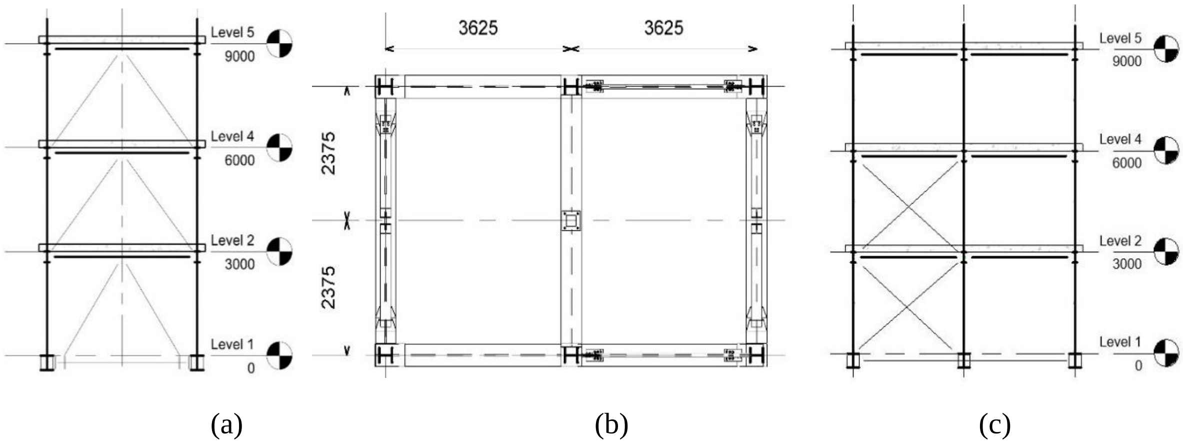

Figure 2: (a) transverse, (b) plan, and (c) longitudinal views of the test structure (mm).

The composite flooring system, ComFlor® 80 (Steel & Tube Ltd.), with trapezoidal steel deck and concrete topping, is used, which is also considered as the permanent load on the structure. The total floor thickness is 150mm while the effective thickness for mass calculation is 121mm. The gravity column base and gravity beam-to-column connections are designed based on the guidelines of SCNZ Steel Connection Guides, Part 1&2 (SCNZ 14 2007), with some modifications (Bagheri 2022). The beam-to-column connections for the bracing bays are pins to provide displacement compatibility for the three RSFJ configurations. 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. The building is assumed to be located in Wellington (soil class C) with importance level of II and about 5 km distant from the nearest fault. All RSFJ configurations are originally designed to accommodate MCE level shaking and 4.5% drift levels, however the test structure itself is optimized in order to accommodate all the tests conducted under the ROBUST program.

1.3 RSFJ tension-compression brace configuration

Four diagonal RSFJ tension-compression braces are implemented on the first and second storey (Figure 3). For RSFJ tension-compression brace assemblies, Anti-Buckling Tubes (ABTs) are provided along with the

RSFJ to mitigate any premature buckling (Yousef-beik et al. 2021). In total, there are four RSFJ per diagonal brace. Each brace consists of a pair of RSFJ at each end. The RSFJ capacities and stiffnesses have been tuned and numerically analysed in such a way that there is no need for braces at the third level. The connections on both ends of the RSFJs in this concept are pinned.

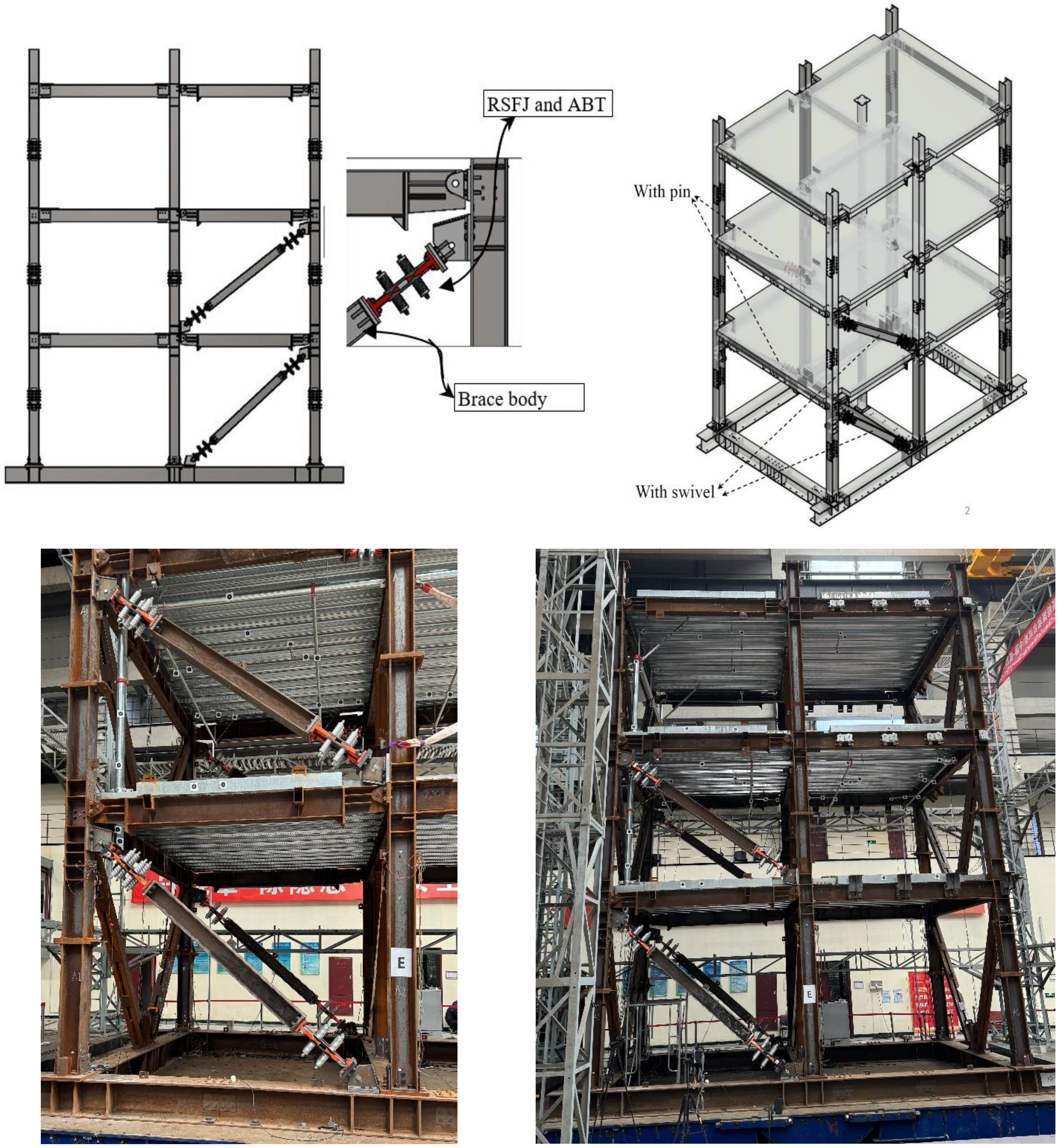

Figure 3: RSFJ tension-compression configuration and brace structure.

1.4 RSFJ tension-only configuration

Eight diagonal RSFJ tension-compression braces are implemented on the first and second storey (Figure 4). In this concept, the RSFJ is combined with a DONOBrace which is a tension-only bracing system. RSFJs are attached at the ends of the diagonal bracing members to provide damping and ductility. The connections on both ends of the RSFJs in this concept are pinned.

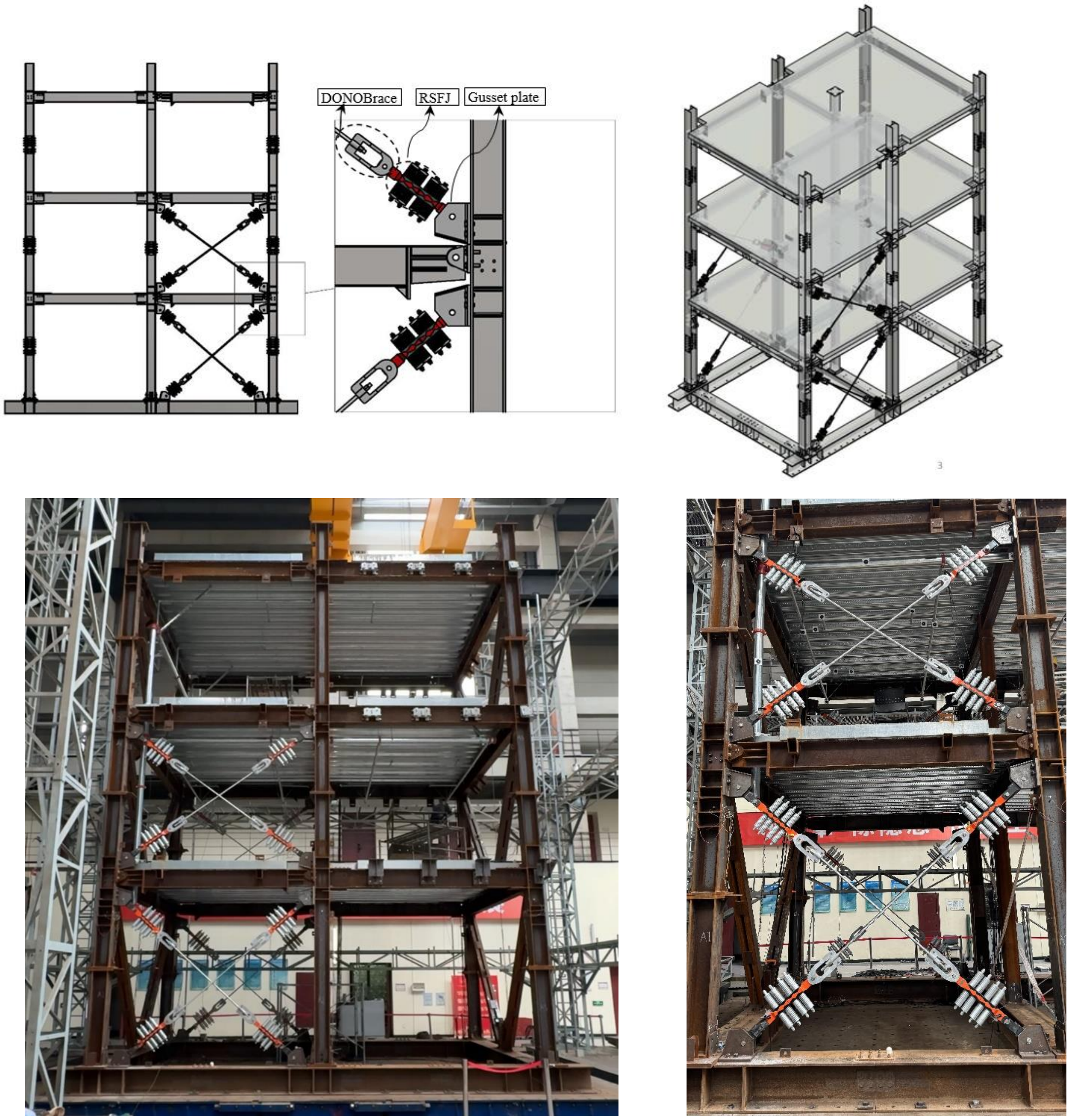

Figure 4: RSFJ tension-only configuration and brace structure.

1.5 RSFJ MRF configuration

In this concept, the RSFJs, as the self-centring components, 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 the other end to end plates provided on the web sides of the beam. The elongation and shortening of the RSFJ will provide the ductility and damping for the system. At the top flange, a pin connection is used in which the pin connects the beam web at the topmost point to cleats which are welded to an end plate; this end plate is then bolted to the column flange. This concept is used in the long direction of the structure and only in one bay; the other bay will employ simple connections. Note that the reason for using one bay only is to prevent the detailing conflict with other concepts being used on the other bay. The MRF RSFJs are used in all stories.

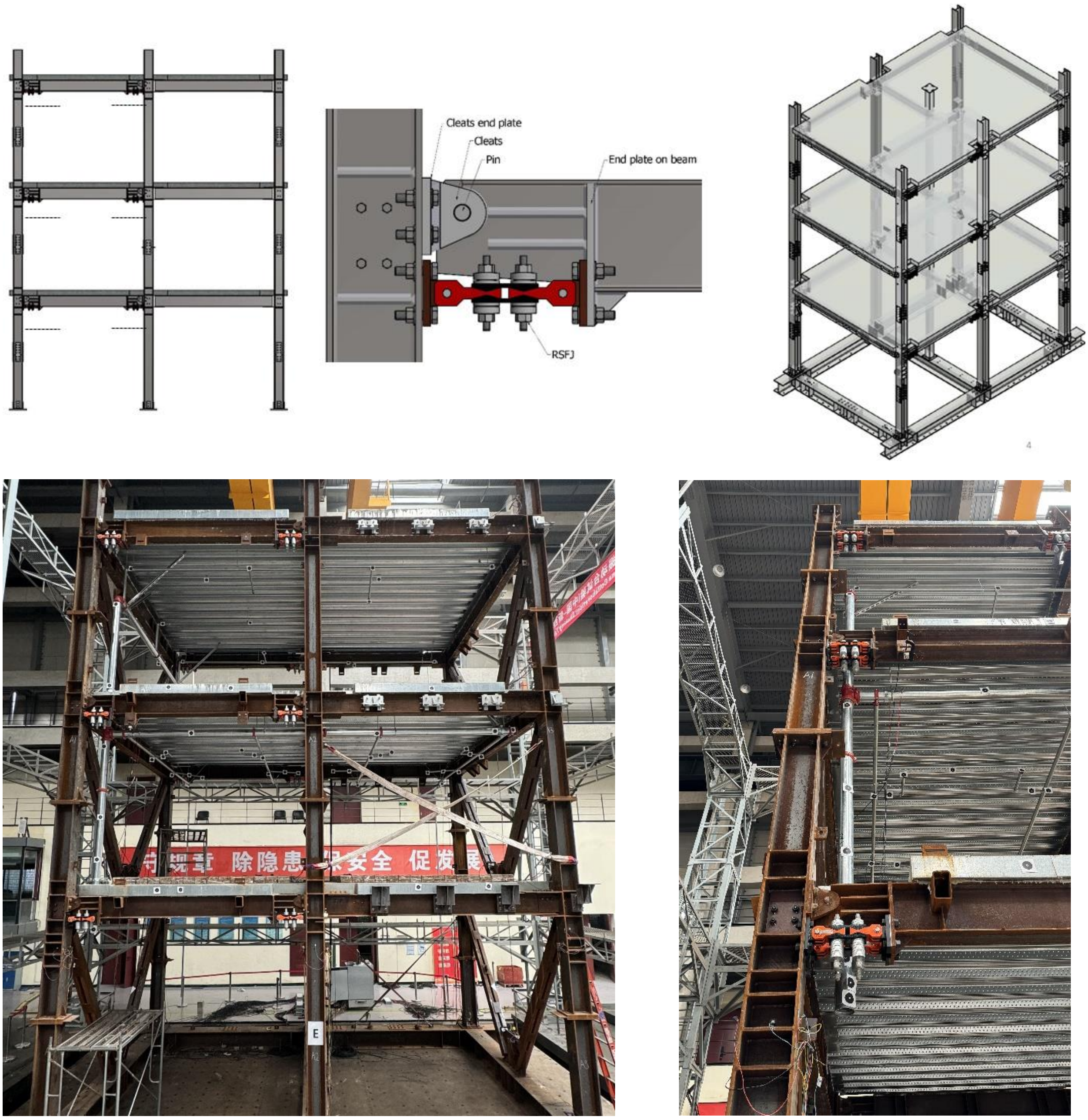

Figure 5: MRF RSFJ configuration and frame structure.

2 TEST METHODOLOGY AND SEQUENCE

2.1 Ground motion selection and scaling

The ROBUST testing program includes several structural and non-structural concepts in its intended test program, so the total number of runs is considerably higher than in a normal test program involving one or fewer concepts. The large number of tests has imposed some limitations on the number of records that can be kept in order to manage the project's timing and funding. Therefore, it was decided to select one earthquake record which matches the target spectrum over the interested period range and scaled it to various shaking levels. For this test, the ground motion Imperial Valley, El Centro 1940, Array #9 station was selected and decided collectively. Scaling range covers periods from 0.4 times the shortest translational structural period to $\sqrt{\mu}$ times the longest translational structural period among all structural systems in the test. The 0.4 and $\sqrt{\mu}$ factors are used to account for the effects of higher modes and nonlinearity on the lengthening of the period.

Scaling has been conducted using a structural performance factor (S_P) of 1.0. The selection criteria and scaling procedures used are fully described in (Bagheri 2022).

2.2 Test Sequence

As part of the ROBUST test series, three RSFJ configuration tests are carried out to assess and observe their performance at full scale structural level under dynamic shaking. Throughout the test, the performance of the RSFJ joints has been the main focus with less emphasis being placed on the overall structural performance. As the structure was designed and optimized to accommodate various seismic resistance systems, including RSFJ configurations, and to withstand extensive shaking tests throughout the ROBUST testing program. All three configurations follow the same testing sequence, beginning with a 180 second white noise shaking to identify the structure's natural frequencies, and in order to ensure that the instrumentation is all functioning and in compliance with safety precautions. The level of excitement is gradually increased beginning with 0.8 times SLS and progressively increasing to 1.2 times ULS in accordance with ROBUST collective agreement. 1.2 times ULS shaking is equivalent to ground motion excitation with peak ground acceleration (PGA) of 0.49g. Both the tension-compression and MRF configurations of the RSFJ are tested unidirectionally as well as bidirectionally, while the tension-only configuration is tested only unidirectionally.

3 TEST OUTPUT

3.1 Tension-compression RSFJ brace configuration

Unidirectional and bidirectional shaking test results are presented separately. Presented results are derived from maximum shaking input for both unidirectional and bidirectional shaking methods, which is equivalent to 1.2 times ULS design level.

3.1.1 Unidirectional loading

A PGA of 0.49g is recorded on the shaking table. Roof displacement of 88mm is recorded, which corresponds to a roof drift of 0.98 percent. The largest interstorey drift recorded at maximum input shaking is presented in Table 1. Considering the measured roof drift and interstorey drift recorded, RSFJs exhibited displacement in alignment with the predicted values for these drifts.

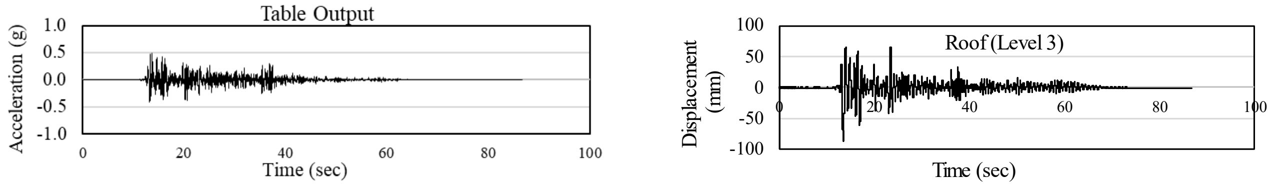

Figure 6: left: shake table output acceleration equivalent to 1.2 times ULS. Right: recorded roof displacement.

Table 1: Maximum storey drift at 1.2 times unidirectional ULS excitation

	Level 1	Level 2	Level 3
Interstorey drift	0.92%	0.98%	1.11%

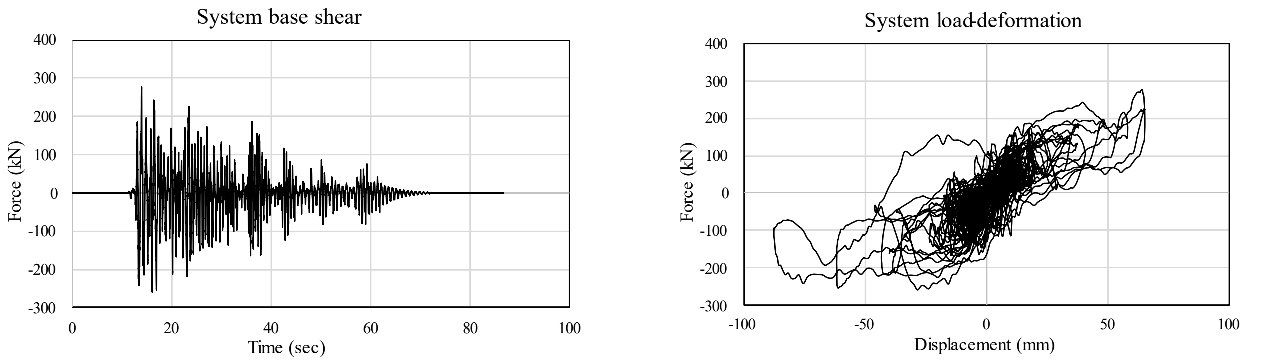

Figure 7: derived base shear vs. time and roof displacement at 1.2 times ULS excitation in the direction of RSFJ bracing.

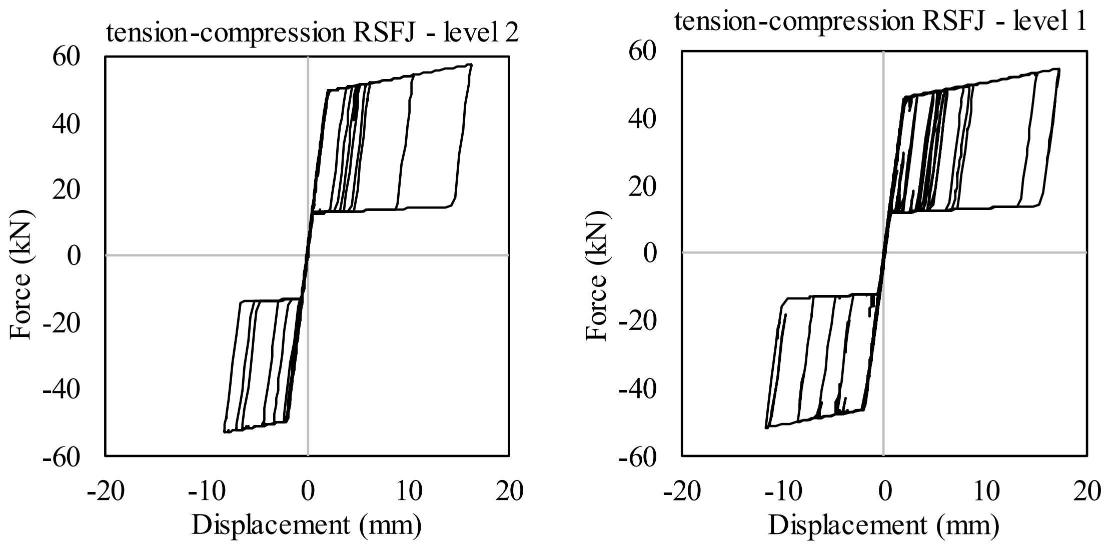

Figure 8: RSFJ load deformation curves at 1.2 times ULS excitation.

3.1.2 Bidirectional loading

A PGA of 0.50g and 0.64g are recorded on the shaking table for the longitudinal and transverse direction respectively, which slightly exceed the target value of 0.49g for the longitudinal direction. Roof displacement of 96mm is recorded, which corresponds to a roof drift of 1.1 percent. The largest interstorey drift recorded at maximum input is presented in Table 2. Considering the measured roof drift and interstorey drift recorded, RSFJs exhibited displacement in alignment with the predicted values for these drifts.

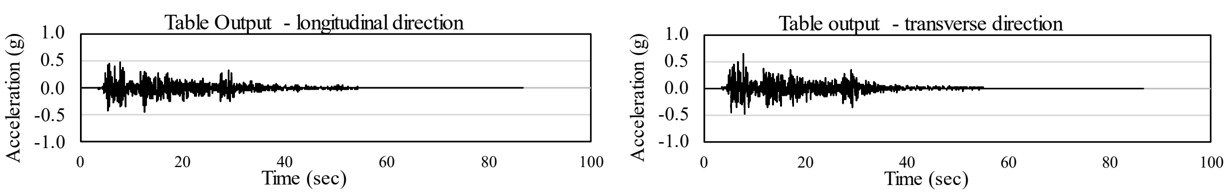

Figure 9: left: shake table output acceleration equivalent to 1.2 times ULS for longitudinal direction. Right: shake table output acceleration exceeded the 1.2 times ULS for transverse direction

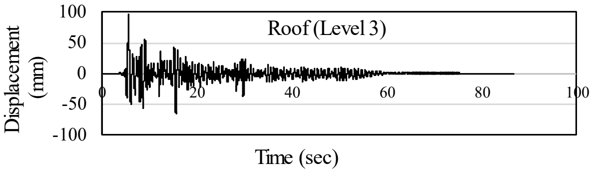

Figure 10: recorded roof displacement at 1.2 times ULS excitation (RSFJ brace direction).

Table 2: Maximum storey drift at 1.2 times bidirectional ULS excitation

	Level 1	**Level 2**	**Level 3**
Interstorey drift	0.88%	1.09%	1.25%

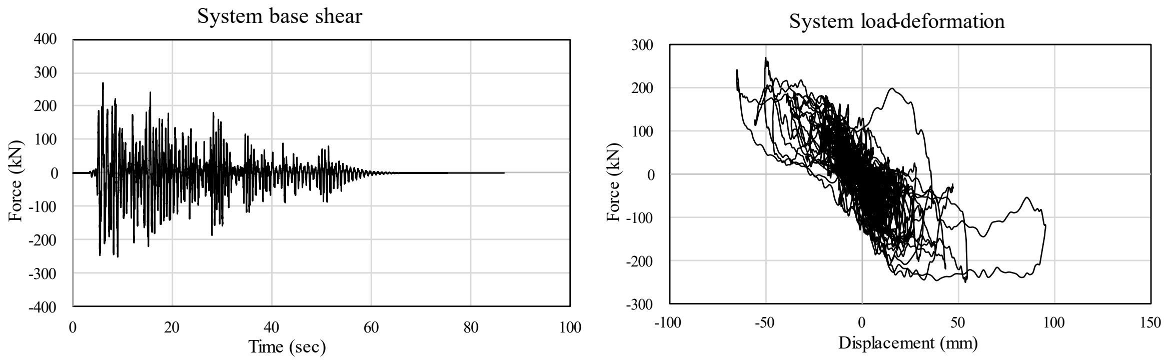

Figure 11: derived base shear vs. time and roof displacement at 1.2 times ULS excitation in the direction of RSFJ bracing.

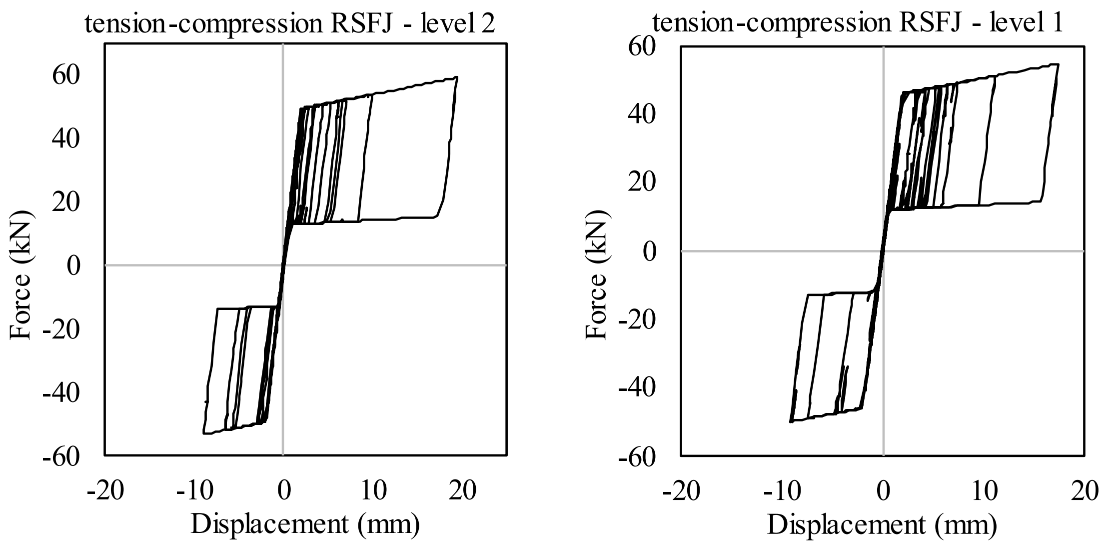

Figure 12: RSFJ load deformation curves at 1.2 times bidirectional ULS excitation.

3.2 Tension-only RSFJ cross bracing

Presented results are derived from maximum shaking input for unidirectional shaking method. A PGA of 0.54g is recorded on the shaking table which is close to 1.32 times the ULS level of shaking. Roof displacement of 60mm is recorded, which corresponds to a roof drift of 0.67 percent. The largest interstorey drift recorded at maximum input is presented in Table 3. Considering the measured roof drift and interstorey drift recorded, RSFJs exhibited displacement in alignment with the predicted values for these drifts.

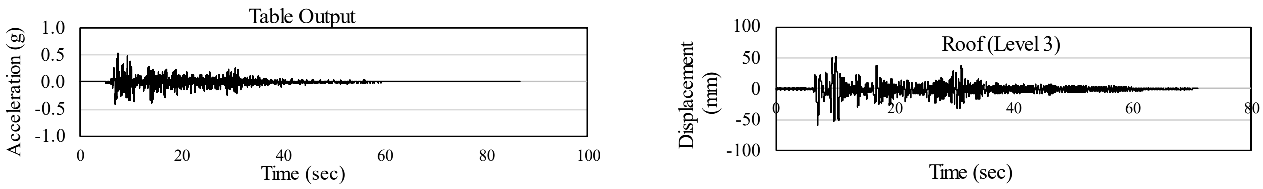

Figure 13: left: shake table output acceleration equivalent to 1.32 times ULS. Right: recorded roof displacement.

Table 3: Maximum storey drift at 1.32 times unidirectional ULS excitation

	Level 1	Level 2	Level 3
Interstorey drift	0.70%	0.64%	0.88%

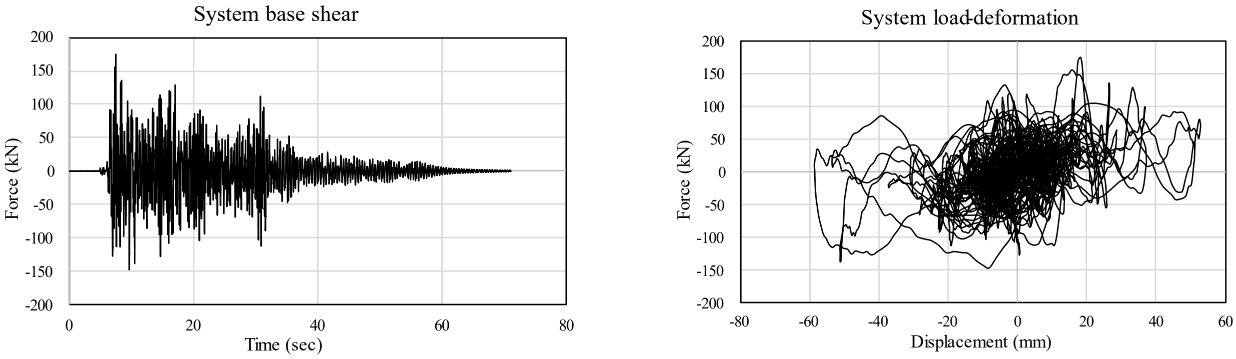

Figure 14: derived base shear vs. time and roof displacement at 1.32 times ULS excitation in the direction of RSFJ cross bracing.

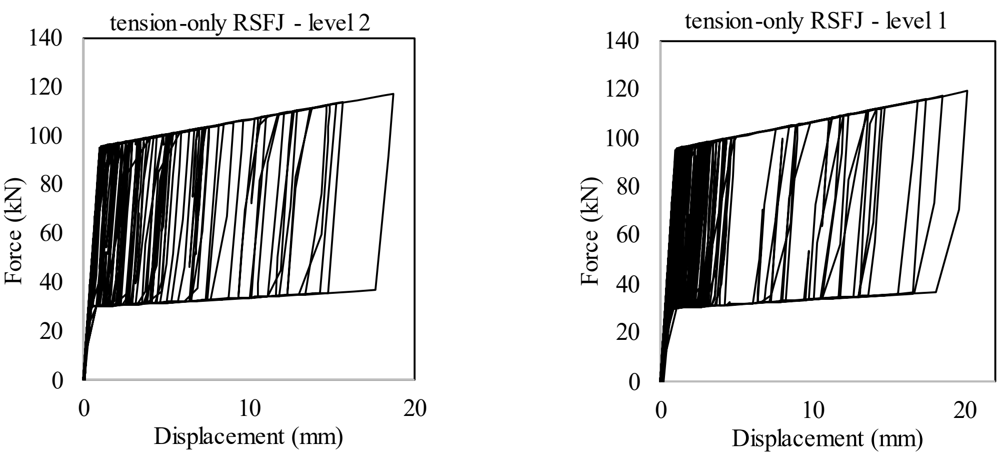

Figure 15: tension-only RSFJ load deformation curves at 1.32 times ULS excitation.

3.3 MRF RSFJ configuration

Unidirectional and bidirectional shaking test results are presented separately. Presented results are derived from maximum shaking input for both unidirectional and bidirectional shaking methods, which is equivalent to 1.2 times ULS design level earthquakes.

3.3.1 Unidirectional loading

A PGA of 0.48g is recorded on the shaking table. Roof displacement of 113mm is recorded, which corresponds to a roof drift of 1.26 percent. The largest interstorey drift recorded at maximum input is presented in Table 4. As a result of the stiff and oversized columns and the concrete floors spanning across two bays continuously in the test structure, the structure has not fully demonstrated pin-pin sway behaviour, resulting in lower displacements for the MRF RSFJs than predicted.

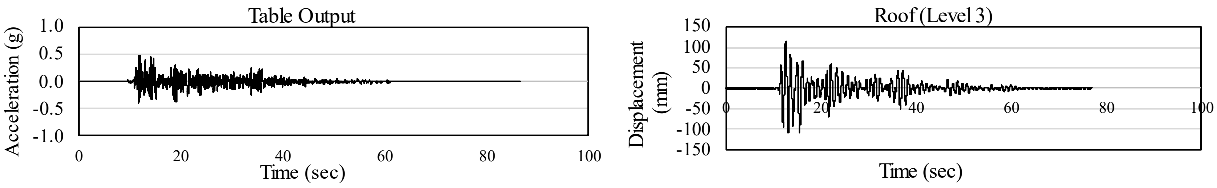

Figure 16:left: shake table output acceleration equivalent to 1.2 times ULS. Right: recorded roof displacement.

Table 4: Maximum storey drift at 1.2 times unidirectional ULS excitation

	Level 1	**Level 2**	**Level 3**
Interstorey drift	1.6%	1.29%	1.1%

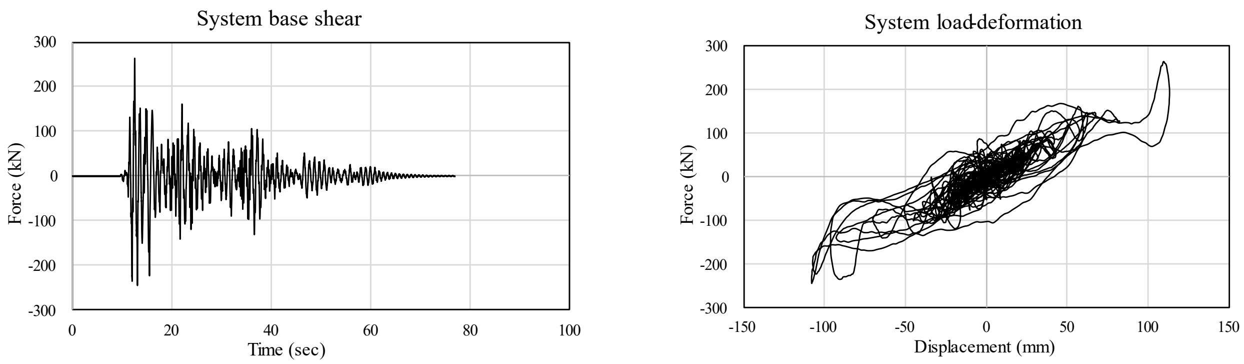

Figure 17: derived base shear vs. time and roof displacement at 1.2 times ULS excitation in the direction of MRF RSFJ frame.

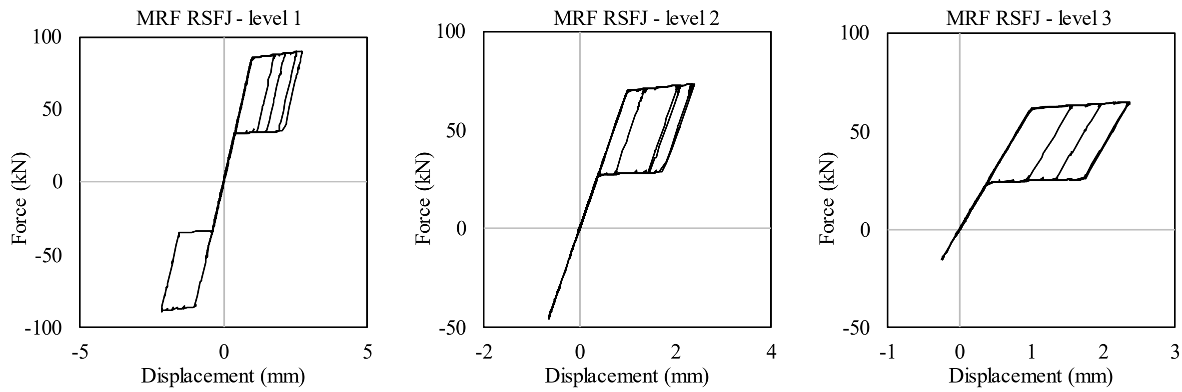

Figure 18: RSFJ load deformation curves at 1.2 times ULS excitation.

3.3.2 Bidirectional loading

A PGA of 0.50g and 0.54g are recorded on the shaking table for the longitudinal and transverse direction respectively, which slightly exceed the target value of 0.49g for the longitudinal direction. Roof displacement of 110mm is recorded, which corresponds to a roof drift of 1.22 percent. The largest interstorey drift recorded at maximum input is presented in Table 5.

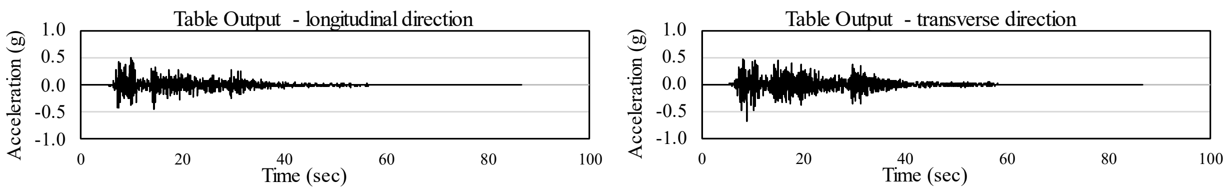

Figure 19: left: shake table output acceleration equivalent to 1.2 times ULS for longitudinal direction. Right: shake table output acceleration exceeded the 1.2 times ULS for transverse direction.

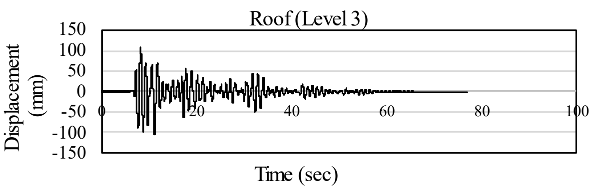

Figure 20: recorded roof displacement at 1.2 times ULS excitation.

Table 5: Maximum storey drift at 1.2 times bidirectional ULS excitation

	Level 1	Level 2	Level 3
Interstorey drift	1.2%	1.29%	1.53%

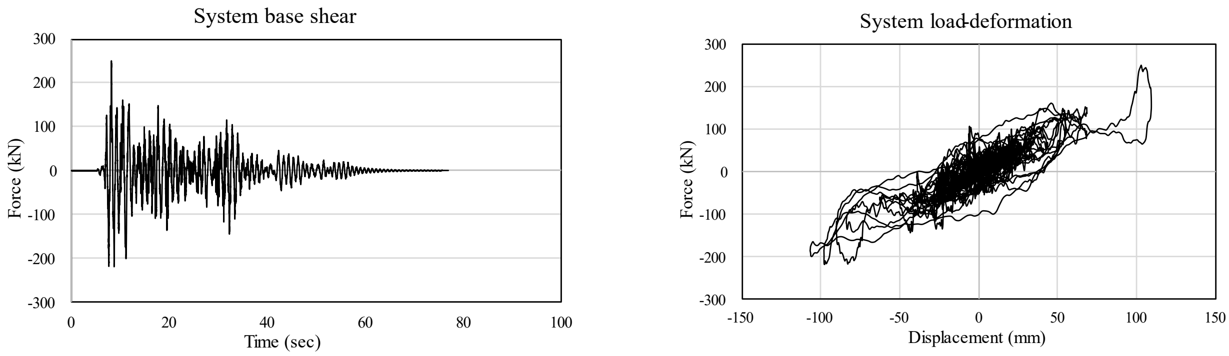

Figure 21: derived base shear vs. time and roof displacement at 1.2 times ULS excitation in the direction of RSFJ bracing.

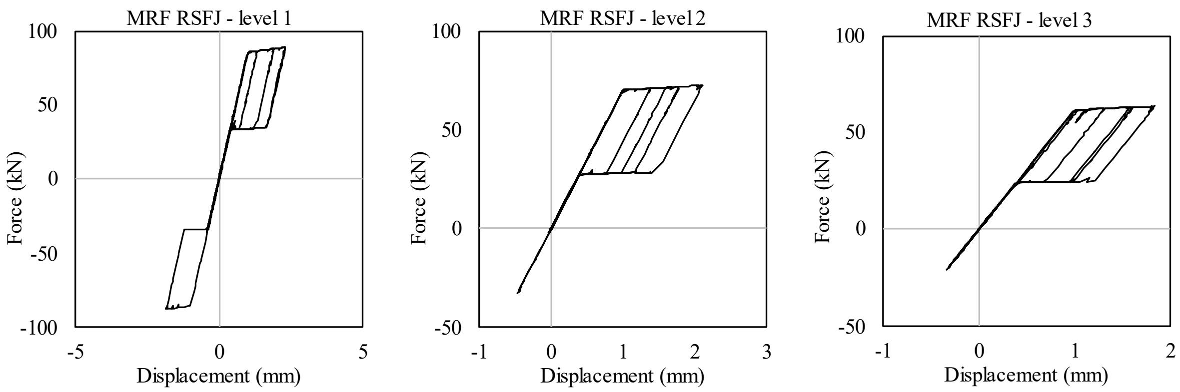

Figure 22: RSFJ load deformation curves at 1.2 times bidirectional ULS excitation.

4 DISCUSSION AND CONCLUSION

In the entire test of three RSFJ congregations, complete self-centeredness is demonstrated. From the smallest magnitude of 0.8 times SLS to 1.3 times ULS, complete self-centring is achieved. Numerically, and now with the tests, it has been demonstrated that RSFJs can be effectively tuned to determine a structure's stiffness and deformation profile. This structure is numerically tuned so that the top story does not require bracing, while distributing the drift demand proportionally, and it is demonstrated that this can be achieved in full scale structures through the tuning of the force-displacement ratio of each RSFJ. In all three configurations, flag-shaped hysteresis is consistent and reliable regardless of the number of shaking excitations. Each of the three configurations demonstrated consistent and reliable flag-shaped hysteresis behaviour across multiple seismic excitations while providing effective damping and energy dissipation capabilities, with no observed damage to the components or structural elements involved.

5 ACKNOWLEDGEMENT

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Finally, the ROBUST consortium would not have been possible without the perseverance, dedication, and collegial collaboration of all involved. The list of authors of this paper is only a fraction of the number of professors, research fellows, doctoral students and others involved in the consortium.

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