QuakeCoRE
NZ Centre for Earthquake Resilience

RoBuSt

DT2 WORKSHOP

Building 119, University of Auckland
Tāmaki Makaurau | Auckland
18 April 2023

RObust BUilding SysTem (ROBUST) Project with emphasis on the Optimised Sliding Hinge Joint

Zhenduo Yan*

*** University of Auckland, Auckland, NEW ZEALAND**

What is ROBUST?

ROBUST is a series of tests on a full-scale configurable friction-based 9 m tall 3 storey steel frame, with non-skeletal elements (NSEs) to demonstrate a resilient building system, a total of 120 + tonnes.

The building incorporates a number of interchangeable seismic resisting systems of New Zealand and Chinese origin. The building has a steel frame and cold formed steel-concrete composite deck.

The testing will provide an exemplar of how economic resilient technology can protect the whole building through novel energy dissipating devices and appropriately detailed NSEs.

The data obtained will provide a rich dataset to validate numerical models and improve design guidelines and standards.

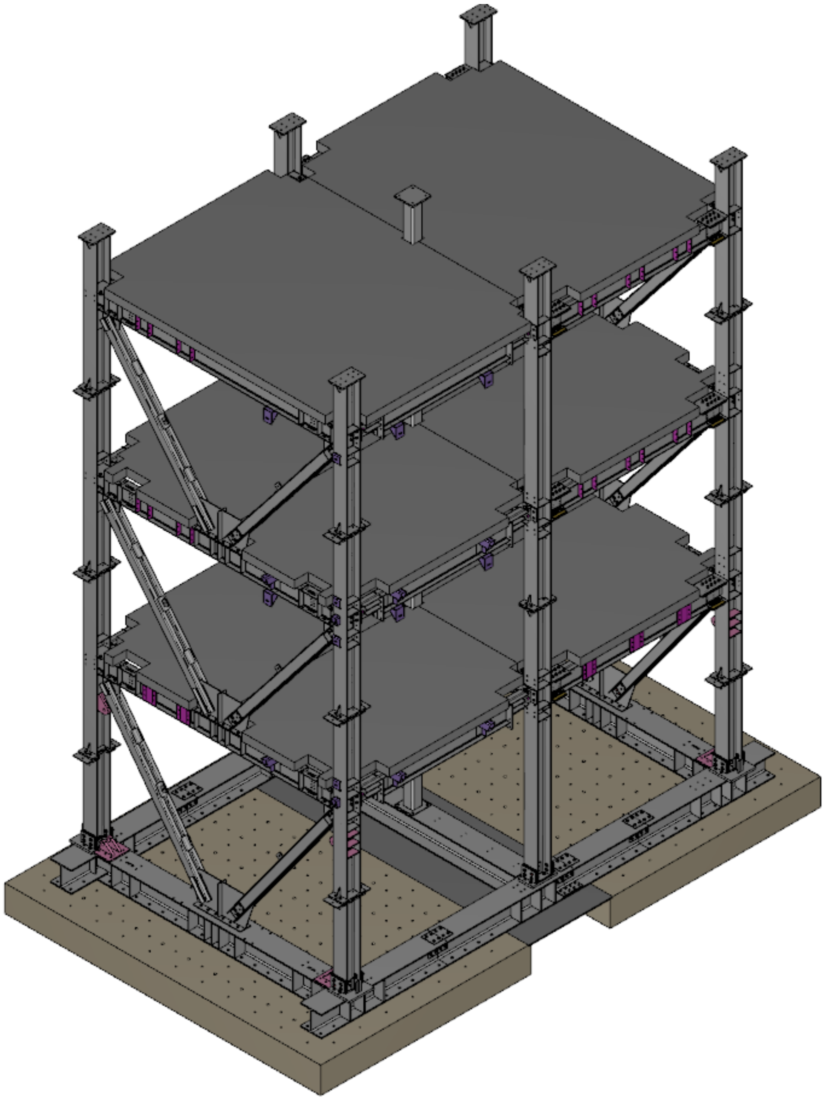


Fig. 1 Tested Structure

What is ROBUST?

Fully Configurable

Resilient Slip Friction Joint (RSFJ)
Prof. Quenneville (UoA)

Asymmetric Friction Connection (AFC)
Symmetric Friction Connection (SFC)
Prof. Clifton (UoA)
Prof. MacRae (UC)
Dr. Ramhormozian (AUT)

Grip N Grab (GnG)
Prof. Rodgers (UC)
Prof. MacRae (UC)

Rocking column
Assoc. Prof. Jia (Tongji)

Non-skeletal elements (NSEs)
Prof. Dhakal (UC)
Assoc. Prof. Xiang (Tongji)

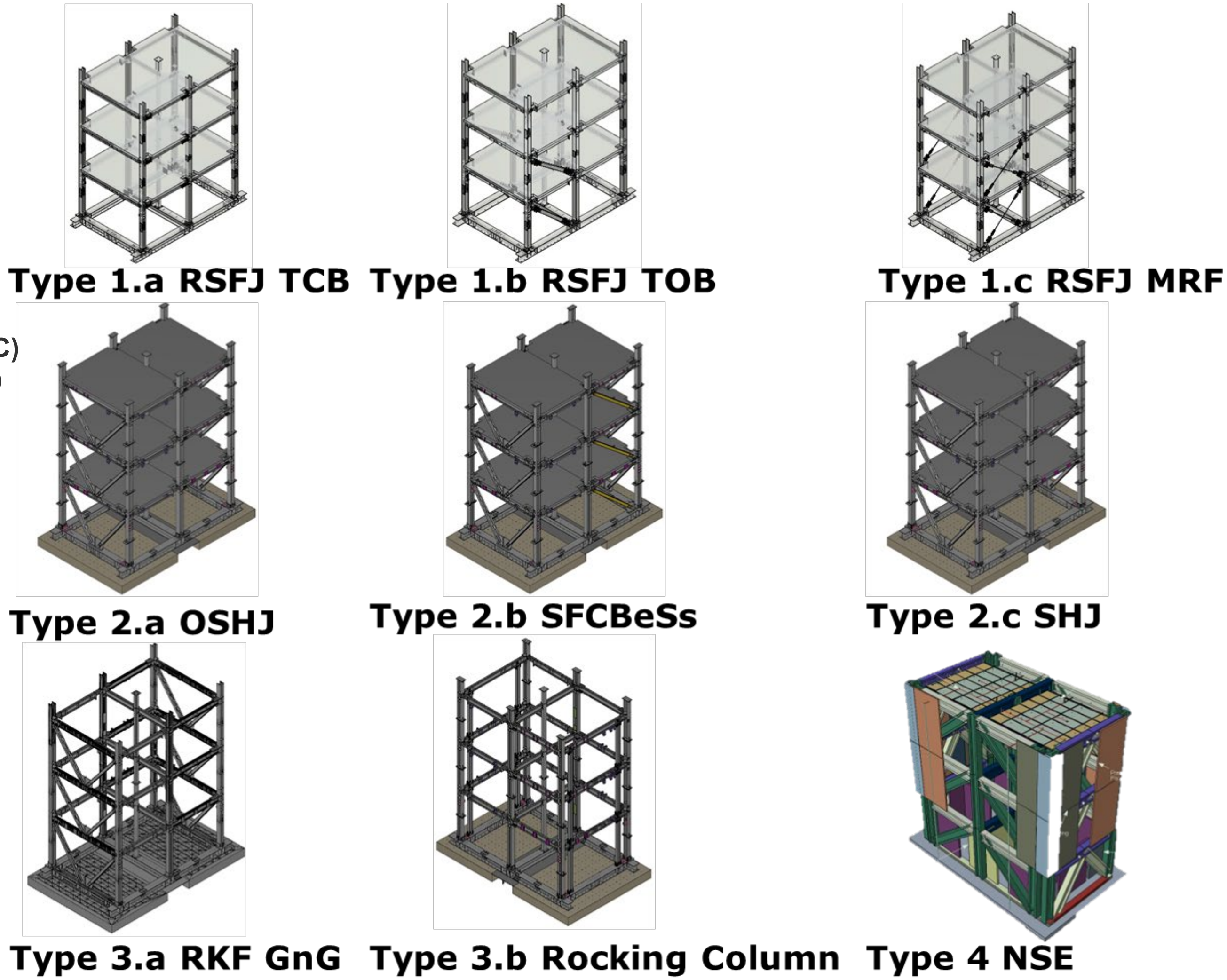


Fig. 2 Structural configurations

What is ROBUST?

The structure is to be tested using two linked bi-directional shake tables at the International joint research Laboratory of Earthquake Engineering (ILEE) facilities, Shanghai, China.

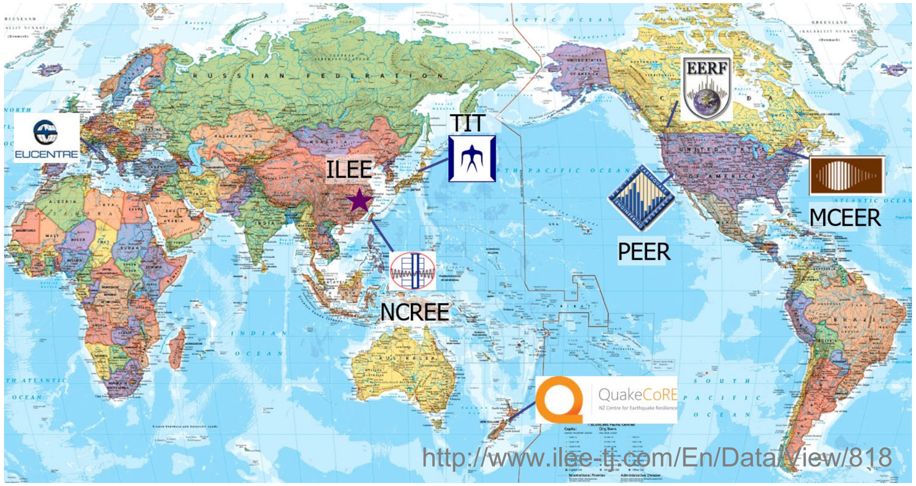


Fig. 3 ILEE partners

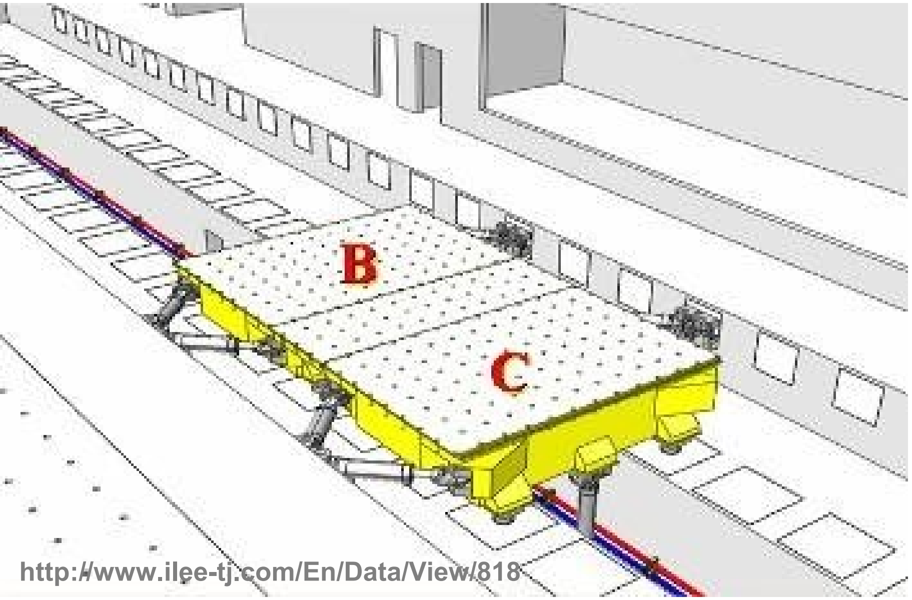


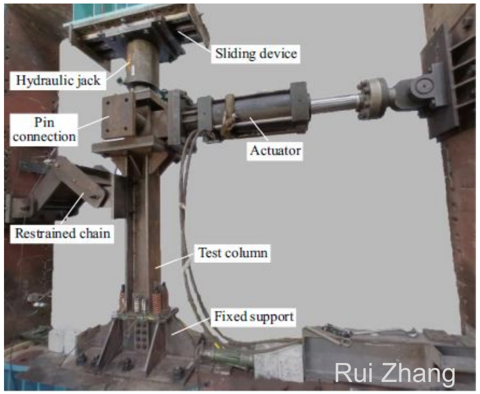
Fig. 4 Linked bi-directional shake tables

Table	Table B and C
Table dimension	6m×4m
Largest payload	70 ton
Degrees of freedom	2 horizontal degrees of freedom
Displacement	500mm both horizontal directions
Velocity	1000mm/s both horizontal directions
Acceleration	1.5 g both horizontal directions
Frequency	0.1 ~50 Hz
Base moment	400 ton·m

What is ROBUST?

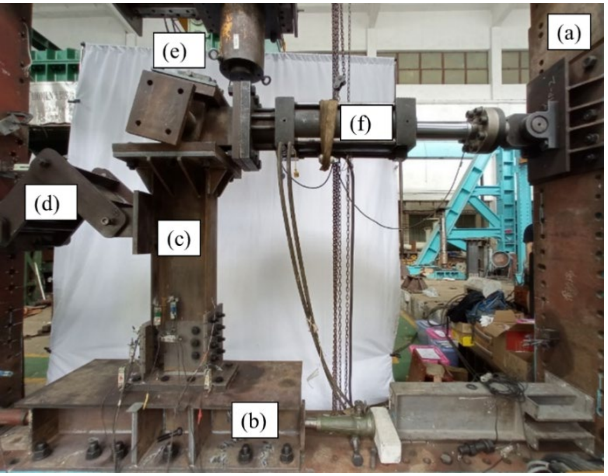
Because of Covid delays to the testing, which have now put this 3 years behind, the first group of students working on this project including myself have had to focus on the design of the structure, component testing and numerical modelling.

(a) RSFJ tension-only brace

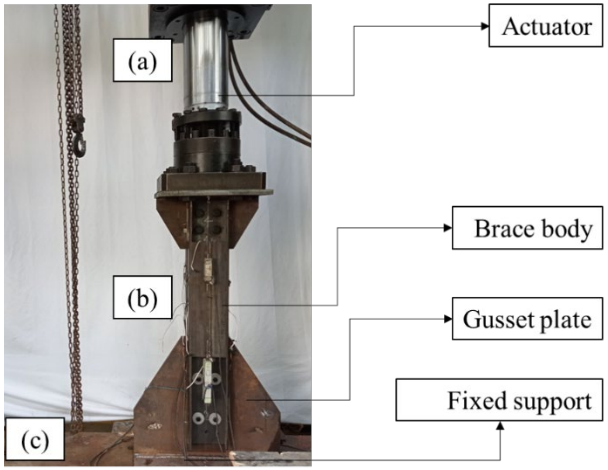


(b) Rocking column

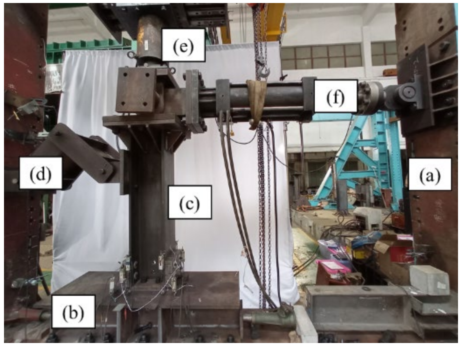
(c) GnG



(d) SHJ/ OSHJ



(e) SFCBeSs



(f) AFC at column base

Fig. 5 Component test

Component test of SHJ/ OSHJ

Moment Resisting Steel Framed (MRSF)
Advantages (compared with braced frames):

- Architectural versatility
- High structural ductility capacity

Disadvantages (compared with braced frames):

- Low stiffness, requiring large members to satisfy drift limits

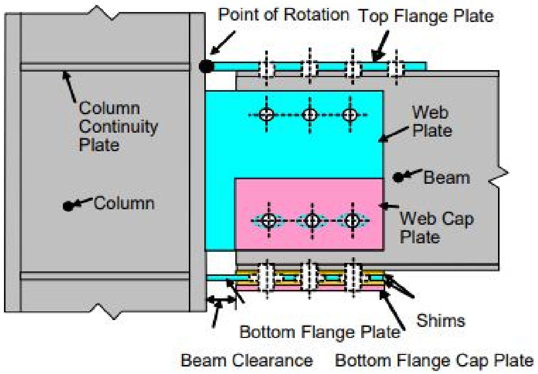
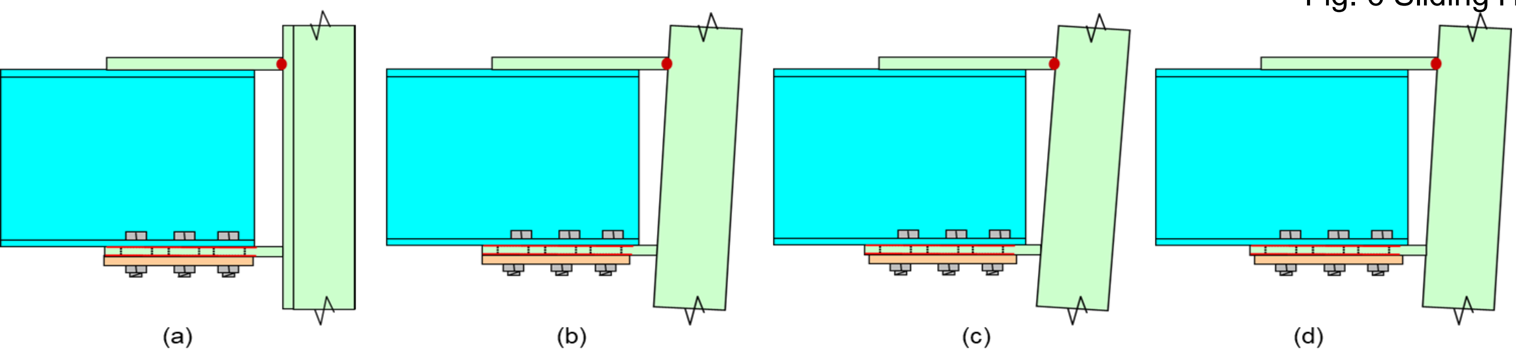
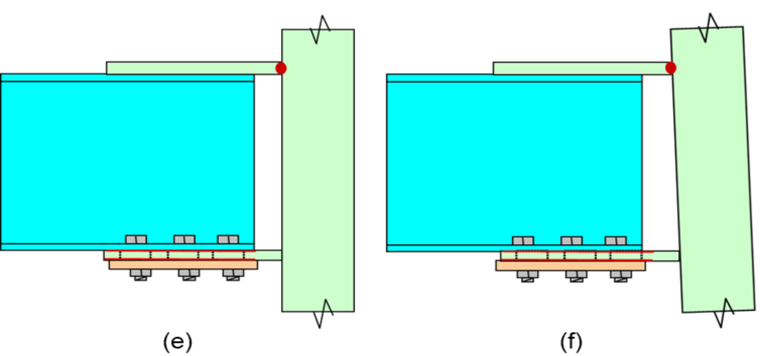
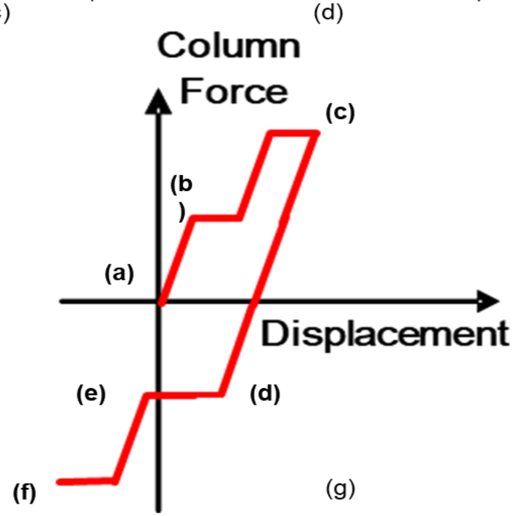


Fig. 6 Sliding Hinge Joint (SHJ) with AFCs







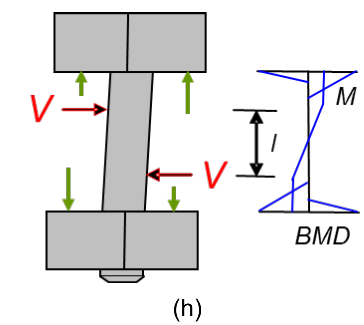


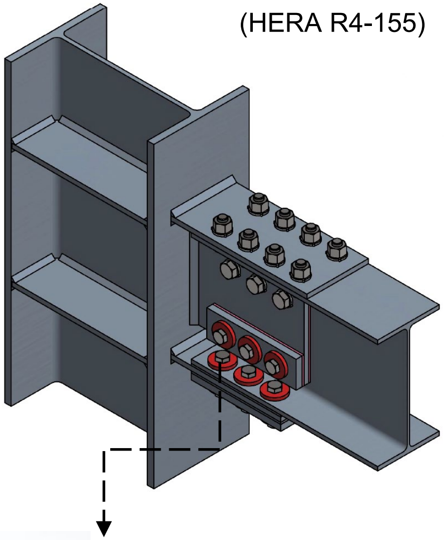
Fig. 7 SHJ concepts

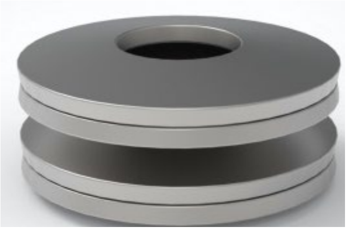
Component test of SHJ/ OSHJ

The OSHJ is the optimized version of the traditional SHJ with Asymmetric Friction Connections (AFCs), with the use of partially squashed BeSs with bolts installed in elastic range, retaining installed bolt tension following severe events.

The sliding shear forces from the AFC bolts at the beam bottom flange level becomes the fuse of the joint, which suppress the yielding of other secondary elements within the design level.

(HERA R4-155)





Peter R.N. Childs, in Mechanical Design Engineering Handbook (Second Edition), 2019

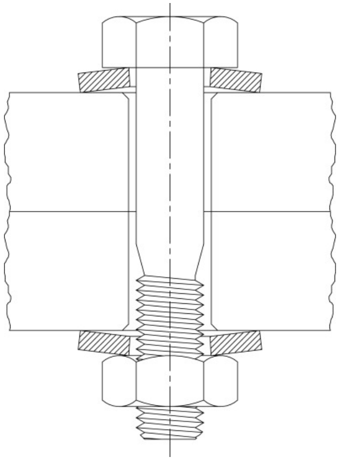


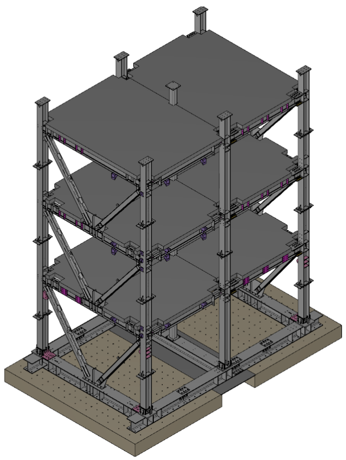
Fig. 8 OSHJ

- ❖ Improved self-centering
- ❖ Retaining the clamping force following severe earthquake events
- ❖ More stable sliding behaviour
- ❖ Eliminating damage prying effects
- ❖ Higher coefficient of friction
- ❖ Less surface degradation

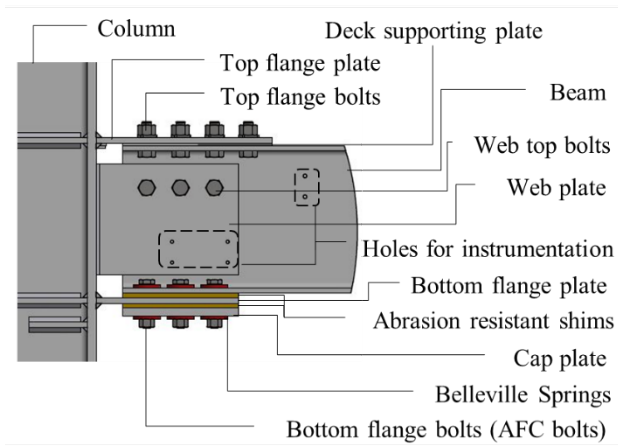
Enhancement of the Sliding Hinge Joint Connection with Belleville Springs(Ramhormozian)

Component test of SHJ/ OSHJ

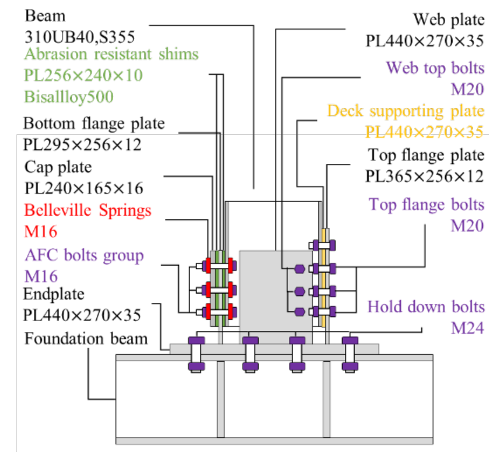
The design of the tested specimen relates to a S355JR 310UB40 beam joining a S355JR 250UC89.5 column which represents the beam-to-column joint at one bay at level 1 of a 9 m tall three-storey MRSF.



(a) tested structure

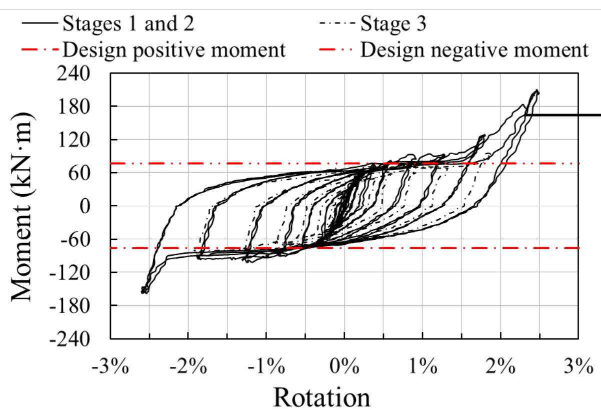


(b) layout



(c) component test

Fig. 9 OSHJ



Bolt bearing end of slotted hole

The OSHJ can seize up and become rigid again following 2 repeated load cases with no repair actions required.

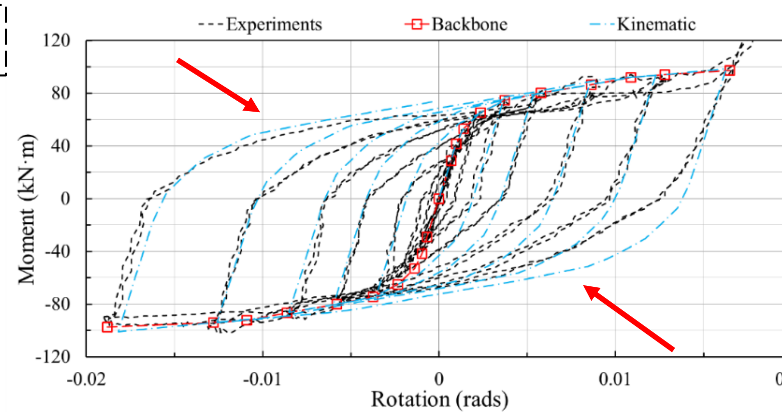


Fig. 10 Experimental results

Fig. 11 Simulated results

Extend the use of BeSs

The concept of using BeSs is further extended to SFC at brace to gusset plate connection and AFC at column base connection.

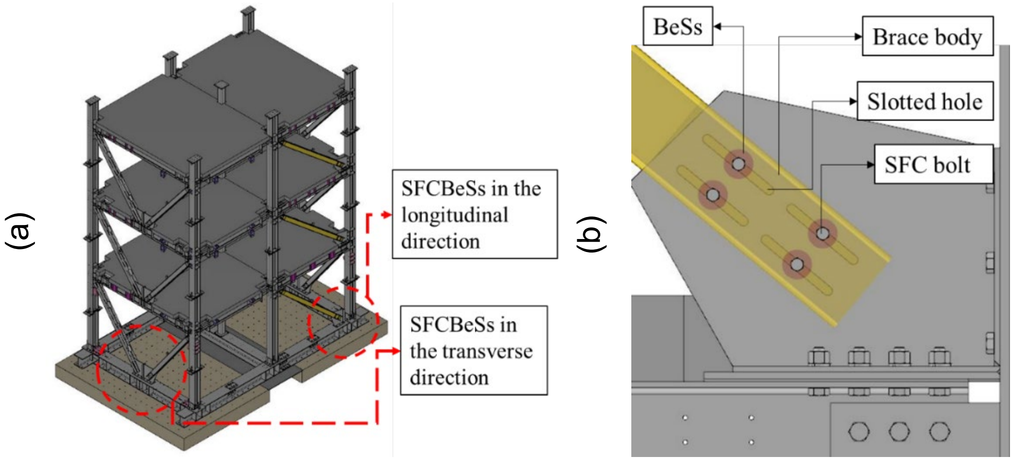


Fig. 12 SFCBeSs at brace to gusset plate connection

- high degree of resilience
- stable and effectively rectangular hysteresis loop
- dissipation of energy through friction
- large deformation capability without structural damage
- limiting the brace axial load to the sliding force

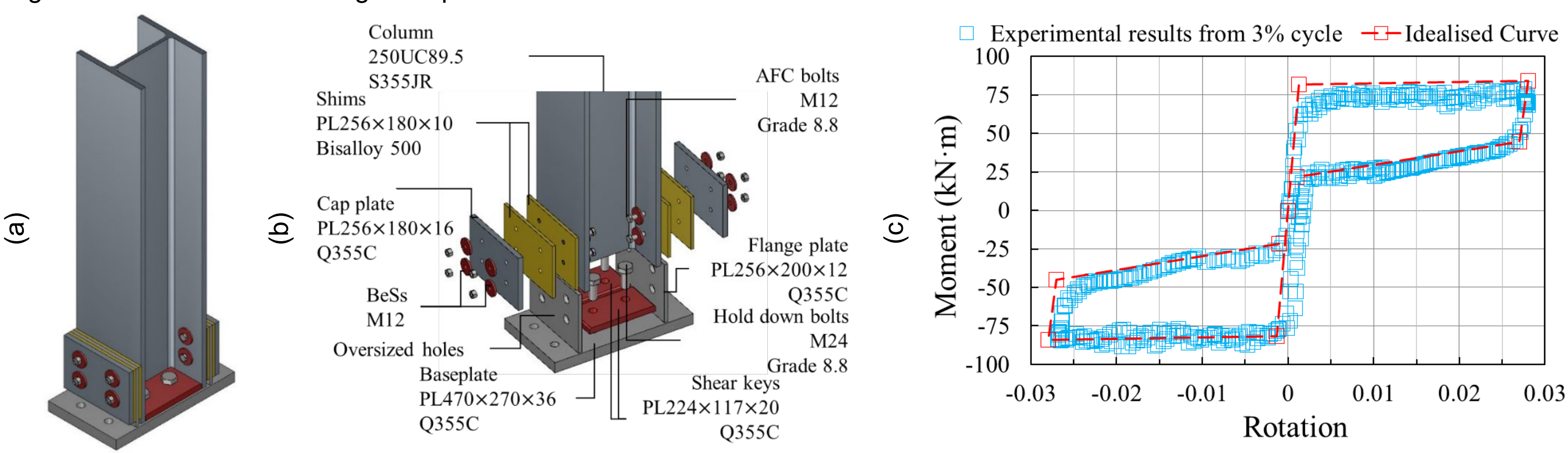


Fig. 13 Column base connection

Link to previous work (partial)

- Charles Clifton (PhD, UoA)

– Semi-rigid joints for moment resisting steel framed seismic resisting systems

- Khoo Hsen Han (PhD, UoA)

– Development of the low damage self-centring Sliding Hinge Joint

- Shahab Ramhormozian (PhD, UoA)

– Enhancement of the Sliding Hinge Joint Connection with Belleville Springs

- Hooman Rezaeian (PhD, UoA)

– Behaviour and design of composite metal deck diaphragm subject to in-plane shear forces

- Behnam Zaboli (PhD, UoA)

– Stability of buckling-restrained brace (BRB) system using a simplified direct analysis method

- Jamaledin Borzouie (PhD, UC)

– Low damage steel column base connections

- Robin Xie (PhD, UC)

– Improved modelling and implementation guidance of energy dissipation devices

- Jose Christian Chanchi Golondrino (PhD, UC)

– Hysteresis behaviour of asymmetric friction connection (AFCs)

- Fahimeh Tork Ladani (PhD, UC)

– Seismic performance of bolted column splice connections in steel moment frames

- Jarrod Cook (PhD, UC)

– Design, testing and simulation of Grip ’n’ Grab ratcheting, tension-only devices for seismic energy dissipation systems

- Ali Abdolahi Rad (PhD, UC)

– Seismic ratcheting of steel low-damage buildings

- And more…

Acknowledgements:

This work described is part of a joint NZ-China research programme with the International Laboratories on Earthquake Engineering (ILEE), Tongji University, Shanghai, China and directly with Tongji University, Shanghai, China. Direct NZ funding is kindly provided by the 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). Administrative support is provided by University of Canterbury (UC). Donations of materials is kindly provided by ComFlor, Hilti Corporation, Tracklok, Gripple, Lanyon & LeCompte Construction Ltd., and Alutech Doors & Windows Ltd. and Catalyst (GNG component tests). Expertise has been generously provided by a number of NZ industry representatives. The authors gratefully acknowledge this support.

MANY ORGANIZATIONS BELIEVE THIS WORK IS IMPORTANT

Thank you

OSHJ

The OSHJ provides a stable hysteric response, remaining rigid under SLS conditions (before the sliding moment is reached) where no sliding in the AFCs is expected. Under the ULS (after the sliding moment is reached), the OSHJ is becomes semi-rigid. The sliding commences in the AFCs allowing beam-column relative rotation to occur about the point of rotation. Energy is dissipated through sliding and the bending moment is limited to a pre-determined value. Strain and stress from beam flange and flange plate show that the protected elements are well within the elastic range.

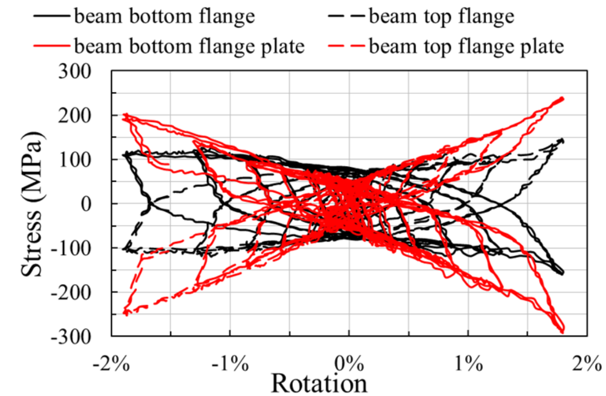


Fig. 12 Stress at both beam flanges

Loading sequence	M_e	$\emptyset M_{OSHJ}$	M_{avg} $(kN \cdot m)$	M_{ult}	$M_{bbm,max}$
Theoretical value	52.6	78.8	78.8	80.9	150
Initial	53.0	73.3	76.4	92.6	210
Severe1	36.4	49.4	68.2	82.2	203
Severe2	37.8	50.7	62.3	75.1	207
Re-installed	39.9	60.8	66.5	86.7	208

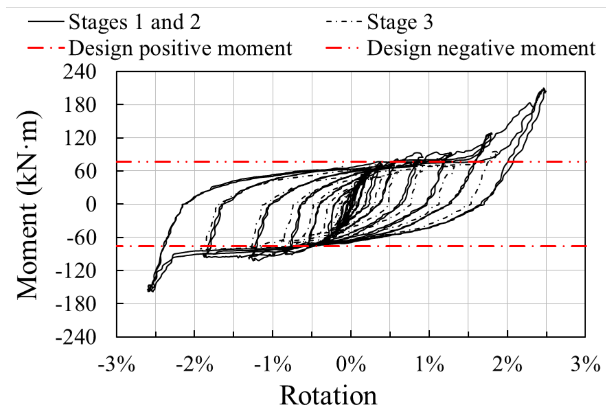


Fig. 13 Moment-rotation hysteretic response

The OSHJ can seize up and become rigid again following the initial and severe1 load cases with no repair actions required. However, a strength reduction of 10.7% from severe1 and 18.5% from severe2 loading sequence comparing to that of the initial loading sequence was observed in terms of average moment resistance with no repair actions taken. This was due to the bolts hitting the ends of the slotted holes. The reduction in terms of design moment resistance is more obvious, 32.7% from severe1 and 30.8% from severe2 with no repair actions taken, due to the same effect.

OSHJ

The preliminary design procedure for the MRF-OSHJ concept followed a similar procedure for that of category 2 MRF with rigid beam to column connections as per cl. 12.10 NZS3404 (1997/2001/2007) and HERA R4-156 (Clifton et al., 2022).

Even though assigned with nominal pinned column base, the contribution from rotational stiffness at column base is not negligible during pushover analysis. A more rigorous and realistic method for determining the initial rotational stiffness of the OSHJ is to be further investigated, as the current method may result in overestimating the stiffness or requiring iterations to an optimum design.

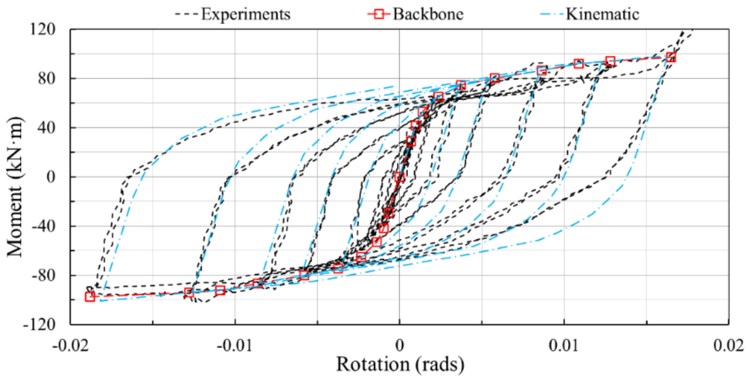


Fig. 15 Comparison with component test results

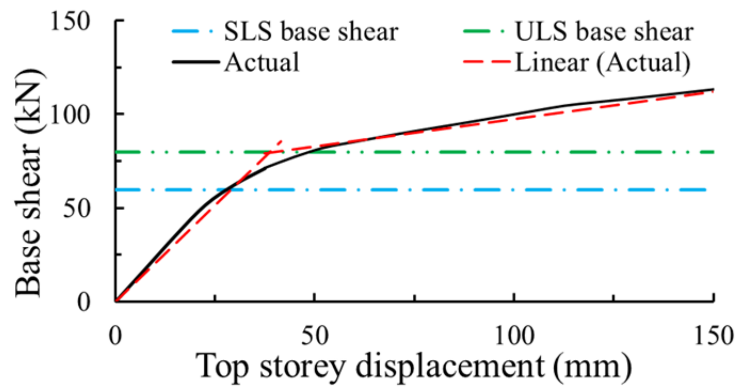


Fig. 16 Pushover curve

OSHJ

The MRF-OSHJ concepts showed satisfying performance under ULS and MCE earthquake records. None of the joints' inelastic demand exceeds the designed value. The distribution of the inelastic demand tends to be evenly distributed under ULS level earthquake. The average maximum residual drift for the MRF-OSHJ is below ±0.14% under ULS events, but exceeds under MCE events. However, the influence of the composite floor slab and NSEs are not considered in the model though positive contributions are expected and the hysteresis curve slightly overpredicts the residual drifts compared with the more accurate OSHJ curve which is not available in SAP2000.

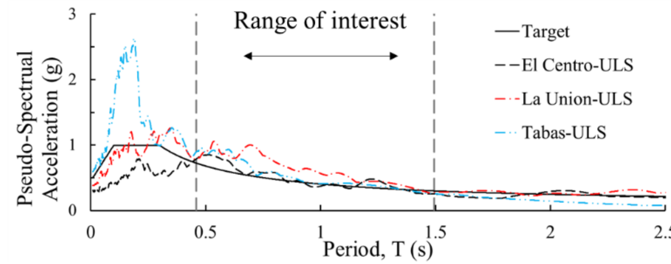


Fig. 19 Selection and scaling of records

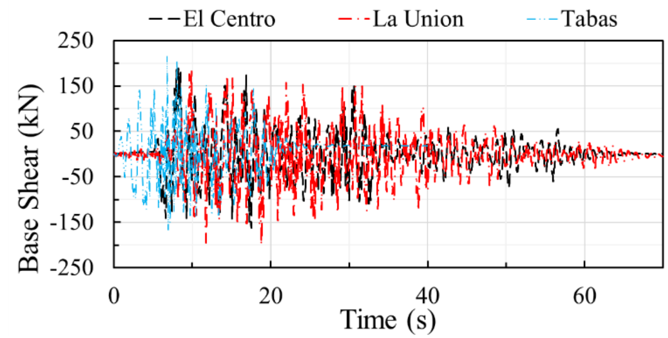


Fig. 20 Base shear response

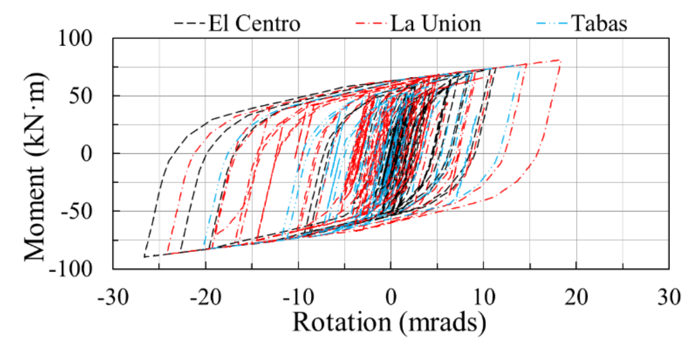


Fig. 21 Joint moment-rotation hysteretic response

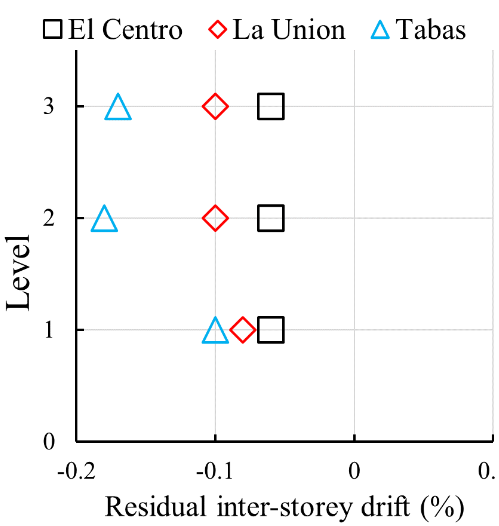


Fig. 17 Residual inter-storey drift

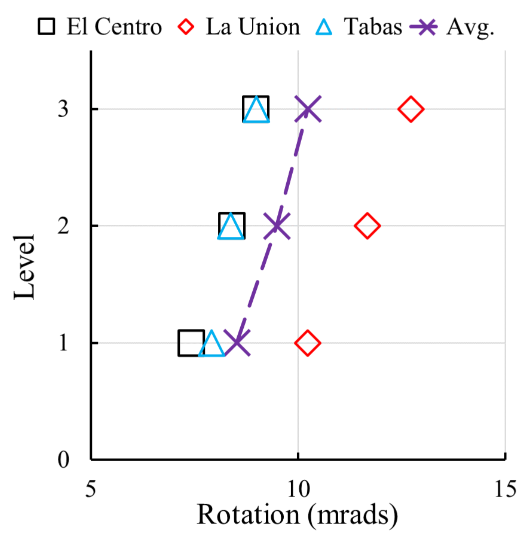


Fig. 18 Joint rotation