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Seismic Performance of Concentrically Braced Frame with Friction Sliding Connections: Learning from Subassembly Component Tests, Numerical Simulations and Shake Table Tests

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ABSTRACT

Concentrically braced frames (CBFs) are one of the common systems to provide load resistance for structures under lateral loads. However, when loaded beyond the elastic range, the brace itself is prone to buckling under compressive axial force and will result in unequal forces in the braces under tension and compression. This is incorporated into current design procedures, but results in reduced performance in severe earthquakes. Several low damage design concepts have been developed and implemented in the recent years to overcome this brace buckling issue. One of these is the use of friction-sliding connections (FSCs) as the dissipative component. CBFs with friction sliding dissipative mechanisms can exhibit inelastic deformation capacity through friction sliding in both tension and compression along the line of the brace, with forces limited to avoid section or member buckling and non-ductile fracture of braces. In a research programme to determine the brace and system behaviour, quasi-static testing on a subassembly of brace-to-gusset plate connection with FSCs was first undertaken to verify its adequate deformation and resistance. The obtained hysteretic characteristics were then adopted in SAP 2000 for numerical simulation of a three-storey CBF. Finally, shake table testing of the three-storey CBF was conducted, including V-bracing and diagonal bracing configurations. This paper reports the key findings from the preliminary design, numerical

simulation, and experimental testing and provides guidance on how to design these systems using current CBF design procedures with appropriate modifications.

Concentrically braced frames with friction-sliding connections

In a concentrically braced frame (CBF), the members are subjected primarily to axial loads. When a conventional CBF responds inelastically to seismic loading, the inelastic demand is concentrated into the braces. Therefore, the inelastic behaviour of the CBF system is very dependent on the effect of inelastic demand on the braces. Inspired by the principle of friction brake pads, in the late-1970's and early-1980's, Pall friction dampers (PFDs) were developed as the pioneering system for controlling the seismic response of buildings through friction devices (Pall, 1979) reducing the initial cost of construction while significantly increasing the earthquake resistance against damage (Pall, 2004). More recently, for enhanced seismic resilience and increased focus on sustainable design, friction devices in different forms have been introduced into braced frames. These devices are designed to be activated before other elements of the structural system, dissipating energy and providing deformation capability while limiting the forces in the protected elements. Some examples used in industry include yielding restrained brace (YRB) equipped with Ten-Co seismic brake from QUAKETEK (2020), DMAX brace with damage free friction joint (DFFJ) from TECTONUS (2023) and the brace installed with a rotational friction damper from DAMPTECH (2021), as shown in Figure 2.

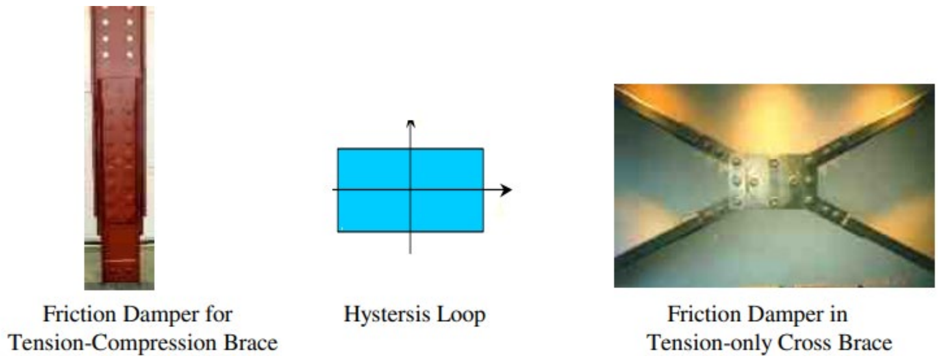
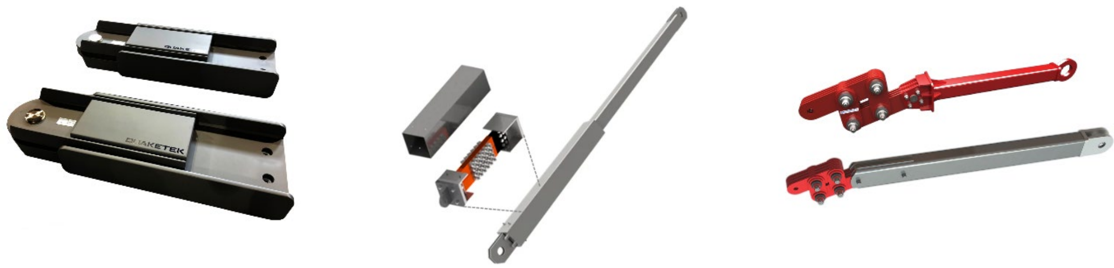


Figure 1: PFDs (Pall, 2004)



(a) (b) (c)

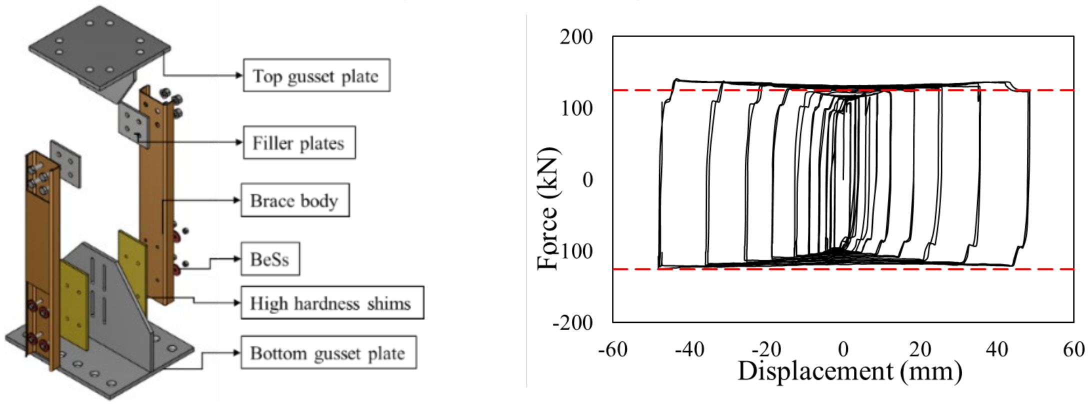
Figure 2: Products from (a) QUAKTECH, (b) TECTONUS and (c) DAMPTECH

General guidance for design and implementing CBFs with friction sliding connections (FSCs) is being included in the next revision of New Zealand Steel Standard (NZS3404), due for public comment release around mid-2025. Currently, the suite of New Zealand standards does not contain end-to-end design methods for CBF with friction dissipative mechanisms that are sufficiently prescribed to allow their inclusion as part of a verification method.

As part of the New Zealand China international collaborative project, RObust BUilding SysTem (ROBUST) Programme (MacRae et al., 2024), experimental testing on FSCs has been undertaken at component level as well as whole of building level on different structural systems including CBFs. This paper reports the key findings and issues from the preliminary design, numerical simulation, and experimental testing.

Component test at brace-to-gusset plate assembly level

The examples of the friction devices mentioned in the previous section include the FSCs as a separate device installed in line with brace. In contrast, in this study, the inclusion of the FSCs in a brace is accommodated in the brace to gusset plate connection, replacing the traditional non-sliding brace to gusset plate connection. Adapting from previous research on friction sliding braces (Ramhormozian et al., 2017), a symmetric friction connection (SFC), a type of FSC, was designed, detailed and installed at the brace to gusset plate connection with partially deflected Belleville Springs (BeSs) and the bolts installed in the elastic range, noted as SFCBeSs. This means long slotted holes are provided on the gusset plate at one end of the brace-to-gusset plate assembly, designated as the sliding end, while the other end with standard holes is the non-sliding end (see Figure 3(a)). Full-scale component tests were conducted to obtain the design strength reduction factor and the overstrength factor. The hysteretic response is shown in Figure 3(b), exhibiting a stable rectangular hysteretic shape, where the red dashed lines indicate the nominal strength. Directly from these component tests, the strength reduction factor is determined as 0.85 and the overstrength factor is 1.15. Due to the limited number of component tests, it is recommended that the design strength reduction and overstrength factors should be 0.80 and 1.20, respectively. More details and results from this testing are reported by Yan et al. (2025a and 2025b).



(a) (b)

Figure 3: Illustration of (a) brace-to-gusset plate assembly and (b) hysteresis loop (Yan et al., 2025a)

Numerical simulation at system level

The V-braced CBF system with bracing effective in tension and compression was designed and detailed in the transverse direction of a three-storey building, as shown in Figure 4(a). SFCBeSs was used at brace-to-gusset plate connection. More details of the three-storey building are reported by Yan et al. (2023). A capacity design procedure was followed, with SFCBeSs being the dissipating system accordance with HERA R4-76 (Feeney and Clifton, 1995/2001) and Cl. 12.12 of NZS 3404 (2007). The stiffness and strength of the brace was decoupled with inelastic behaviour occurring at the joint and the brace remaining elastic. Therefore, the C_s factor, taking account for less satisfactory inelastic behaviour of the CBF systems due to compression brace buckling, was be taken as 1.0. The brace size was first selected to control the required seismic lateral deflection, then to check against the overstrength action of the SFCBeSs. In addition, as the brace shall not buckle with the presence of SFCBeSs, the difference between overstrength capacity and the design capacity of the SFCBeSs was used to determine the net vertical seismic force applied to the collector beam for each considered level at the brace/ collector beam joint. This is an important requirement to suppress collector beam plastic hinging.

Numerical simulation in 3D was conducted by Yan et al. (2023), taking the brace with SFCBeSs as a two-joint link element with uniaxial plasticity using plastic (Wen) model in SAP 2000. Three records were selected and scaled as recommended by Oyarzo-Vera et al. (2012) for the North Island of New Zealand. The damping type considered for the nonlinear time-history analysis is the Rayleigh-type proportional damping, considering 5% of critical viscous damping for the first two modes. Results from non-linear time-history analysis showed a ratio of average base shear under maximum considered earthquake (MCE) excitation to that under design level ultimate limit state (ULS) excitation was 1.25. Moreover, the MCE to ULS drift is 3.57. The average maximum residual drifts measured from roof level under MCE (0.07%) was found to be less than that under ULS (0.11%), below the 0.14% limit reported by Clifton (2013).

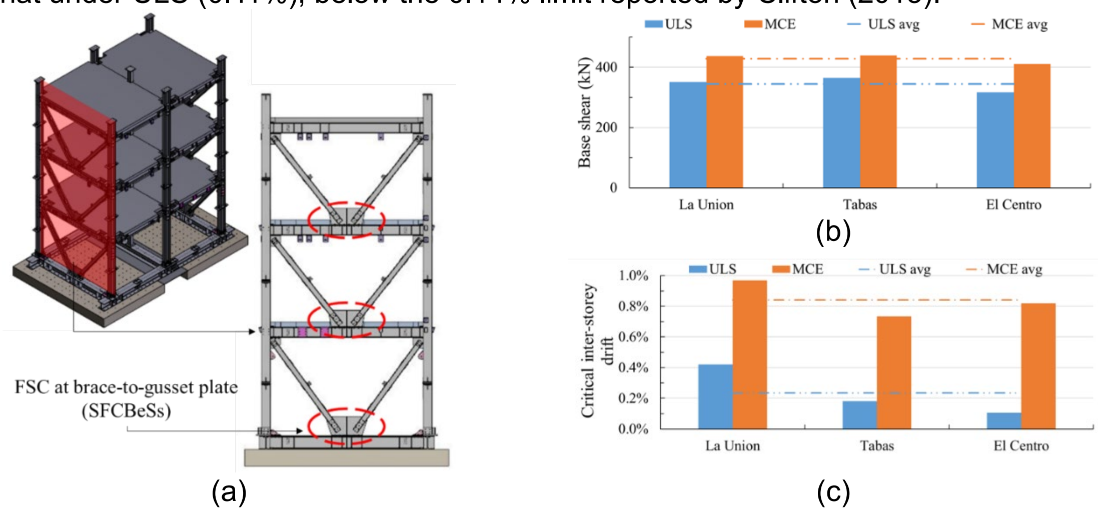


Figure 4: Illustration of (a) consdiered structure, maximum and average of maximum (b) base shear and (c) critical inter-storey drift (Yan et al., 2023)

Shake table testing at system level

Shaking table testing was conducted of a near full scale three-storey steel frame composite floor building, with 3 m inter-storey heights and a centreline plan dimension of 7.25 m by 4.75 m. The isometric view of the tested building is shown in Figure 5(a). Two bracing configurations were tested using single diagonal bracing as shown in Figure 5(b) and V-bracing as shown in Figure 5(c). Both configurations were designed with SFCBeSs at the brace-to-gusset plate connection, dissipating energy through frictional sliding under design level ULS events.

The base shear response under design level service limit state (SLS) and ULS are shown in Figure 5(d) and Figure 5(e) for diagonal bracing and V-bracing configurations, respectively. For the V-bracing configuration, the recorded ULS base shear was 321 kN very close to the average base shear obtained from numerical simulation of 344 kN in Figure 4(b). The roof residual drift was found to be 0.02%, less than that predicted in the numerical model of 0.11%. The diagonal bracing configuration experienced more displacement in the positive direction (South), as shown in Figure 5(d). However, this didn't result in a high residual drift, as the roof residual drift under ULS shaking for the diagonal brace configuration was almost zero, 0.005%. For both bracing configurations, there was no change in fundamental period and no visible damage observed at the conclusion of the tests.

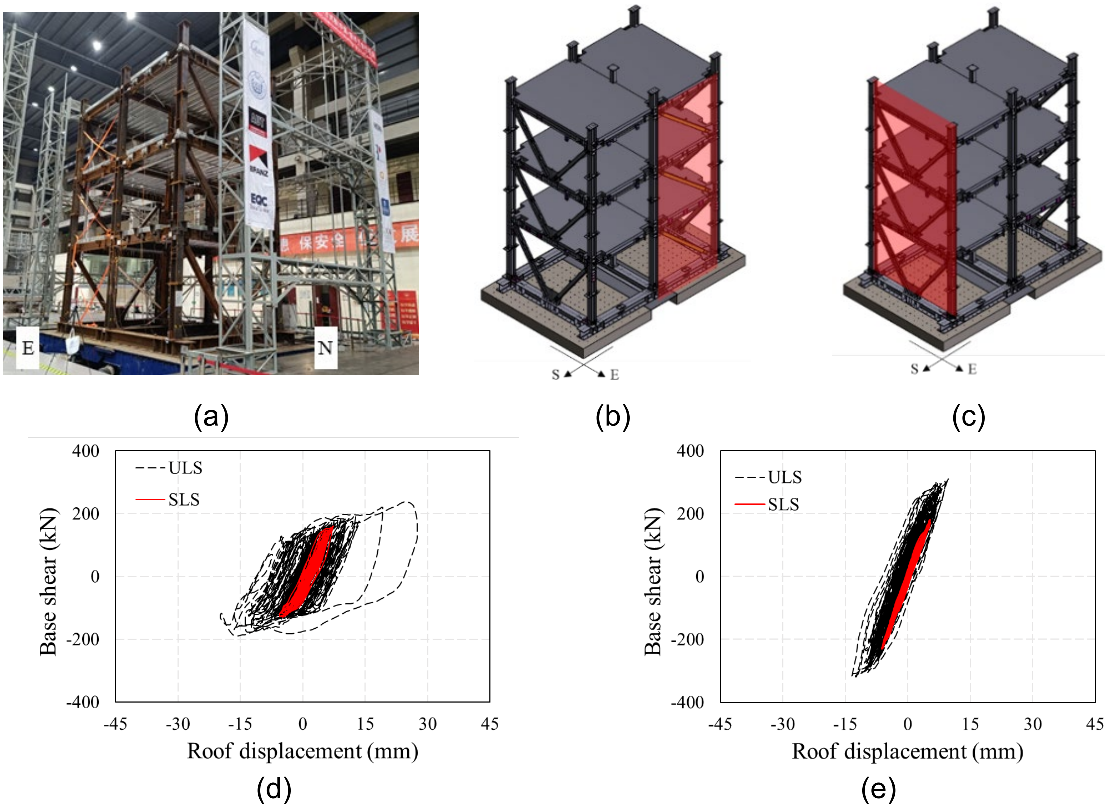


Figure 5: Illustration of (a) tested structure and (b) diagonal bracing configuration, (c) V-bracing configuration, base shear response of (d) diagonal bracing and (e) V-bracing configuration (Yan et al., 2025a)

Summary

This paper presented the key findings from the preliminary design, numerical simulation, and experimental testing of CBF with FSCs. Overall, the performance of the tested three storey CBF was satisfying, providing reliable and adequate deformation capacity and resistance at both component and system levels, showing the low-damage characteristics. The non-linear deformation of the system occurred through friction sliding along the line of the brace, with the brace being designed for the overstrength actions from the FSCs, keeping the brace elastic and non-buckling. The experimental recorded base shear was found to be close to the average base shear from numerical simulation under design level. However, it was found that the residual drift recorded from shake table test was much less than that estimated from numerical model (0.02% comparing to 0.11%). FSCs can be incorporated into CBFs based on the current design provisions with careful consideration on load path and connection detailing. A detailed worked example has also been prepared and is presented in an international journal article (Yan et al., 2025b) that is currently under review at the time of writing this paper. Interested readers are encouraged to consult the article once it becomes available.

Parametric studies are underway to study and quantify other key design parameters, for example distribution of lateral resistance, height restriction and bracing configuration, which targets to relax the current limit for applications in height and number of storeys.

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