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Experimental test of a new self-centring tension-only brace using the Resilient Slip Friction Joint

H. Bagheri, A. Hashemi & P. Quenneville

The University of Auckland, Auckland.

S.M.M. Yousef-beik & P. Zarnani

Auckland University of Technology (AUT), Auckland.

ABSTRACT

A new self-centring tension-only brace has been introduced and experimentally tested in this research. The proposed brace employs Resilient Slip Friction Joint (RSFJ) at the end(s) of the diagonal cross braces that provides self-centring and energy dissipation characteristics and removes pinching behaviour and post-yield slackness (which is common for the conventional tension-only braces). By implementing this system, the brace and the inclusive structure will remain damage-free with no after-event maintenance. A simple full-scale 2D steel braced frame with dimensions of 3.1 m high and 5 m long was designed to accommodate Ultimate Limit State (ULS) and Maximum Considered Earthquake (MCE) drift levels, 2.5 and 5%, respectively. Then, the joints were designed and component tested and finally the frame was tested using static and dynamic loading protocols. The test results showed a repeatable flag-shape behaviour for the frame at different amplitudes of both protocols; the dynamic effects were observed and a solution was proposed to mitigate these effects. Since no component yields and there is no residual drift even up to the MCE level, the proposed tension-only brace can reduce significantly the structural damage which is also simple to design and use in new and existing structures.

1 INTRODUCTION

This paper focuses on introducing a new damage-avoidance seismic tension-only brace and demonstrating its performance through full-scale experimental tests. The proposed system has Resilient Slip Friction Joint (RSFJ) at the end(s) of the cross braces which features/adds energy dissipation and self-centring properties to the system. The current tension-only braces suffer from pinching and slackness behaviour since they are

supposed to yield in tension and buckle in compression. These subsequent cycles of tensile yielding and compression buckling generate pinching and post-yield slackness in the system and make the conventional tension-only braces seismically unreliable. In comparison, the introduced tension-only brace suffers no pinching and slackness and in addition, the self-centring and energy dissipation is also provided. As such, it paves the path towards having a resilient structure by reducing the risk of the significant costs for retrofitting, demolishing and rebuilding after major events. In other words, it is a prominent effort for making low-damage structural construction available. The RSFJ has been previously developed and the governing design equations are derived; so, this research focuses on developing a new application of the joint, tension-only brace, and demonstrating its experimental performance in a full-scale two-dimensional steel frame under static and dynamic loads.

The fundamental issue with the conventional structures is that earthquake energy is dissipated through damage to structural systems which renders the structure unusable after the seismic event. (Wang et al. 2013) introduced a Tension-Only Concentrically Braced Beam-Through Frame (TOCBBTF) that would undergo tensile yielding and compression buckling which consequently would result in residual drift and a pinching behaviour. In order to enhance the performance of this system through preventing the formation of soft-story mechanism and providing a more uniform drift profile, first a rocking core was added to this system by (Hu, Wang, and Qu 2018) and later on (Wang et al. 2018) introduced self-centring modular panels (SCMP) which offer lateral stiffness and self-centring for the TOCBBTF. After observing huge demolitions in the Michoacan earthquake in 1985 (Qiu and Zhu 2017) and Christchurch, New Zealand in February 2011, massive amount of research has been devoted to developing low-damage structural systems and related design methodologies. (Clifton et al. 2007) and (MacRae et al. 2010) developed sliding hinge joint (SHJ) for steel moment frames in which the energy, rather than being dissipated through damage to primary structural members, is dissipated through friction between steel plates as the rotation is accommodated by sliding of these plates on each other located at the bottom flange of the beam. Self-centring systems with damping characteristics are the state-of-the-art research and practice in the low-damage seismic systems. Later on, (Khoo et al. 2012) used friction ring springs in order to add self-centring properties to SHJ. (Christopoulos et al. 2008) introduced a new Self-Centring Energy Dissipative (SCED) brace by using post-tensioned rods alongside with an additional source of friction damping that relied on a thin friction pad sliding over a stainless steel surface. They carried out component tests, full-scale (reduced length) quasi-static axial tests, and quasi-static and dynamic seismic tests on a full-scale frame in their research. Results of their research confirmed the validity of equations developed for the behaviour of the proposed brace and the viability of the concept as an alternative for the current braced frame systems. (Erochko et al. 2014b) proposed a telescoping layered revised version of SCED that was tested up to 4% drift still presenting self-centring capability. The purpose of that research was to enhance the displacement capacity of the SCED brace. Afterward, (Zhu and Zhang 2008) introduced a self-centring friction damping brace (SCFDB) for use in concentric braced frames (CBF). They used Nitinol wire strand as the restoring element and the slip friction between the pre-stressed blocks as the energy dissipation mechanism. They numerically compared the proposed system with buckling restrained brace (BRB) by nonlinear dynamic analysis and concluded that this system can achieve seismic response comparable to that of BRB while improving significantly the residual drift issue. (Miller et al. 2011) proposed a self-centring BRB (SC-BRB) by introducing pre-tensioned super-elastic NiTi shape memory alloy (SMA) rods to re-centre the system. The SMA rods will elongate as the brace is under tension or compression. They investigated the behaviour and performance of the SC-BRB by applying cyclic loading protocol adapted from the AISC 341 Seismic Provisions for Structural Steel Buildings (AISC 341-10 2010) over a half-scale specimen. In order to address the pinching behaviour in conventional tension-only braces, (Araki et al. 2016) utilized super-elastic SMA. In that research, a stopper was used to restrain the deformation of the SMA bars and to prevent premature fracture of the SMA bars against unexpectedly large earthquakes. In order to experimentally demonstrate the performance of this system, they conducted

component and shaking table tests. Test results demonstrated that the SMA braces are effective to prevent pinching and residual deformations.

2 RSFJ AND ITS APPLICATIONS

RSFJ is a self-centring energy-dissipative joint invented by (Zarnani and Quenneville 2015) which can be used in various lateral load resisting systems of steel, concrete, timber, and hybrid structures and has recently been introduced to New Zealand construction industry. It comprises of grooved middle and cap plates, disc springs and high-strength bolts/rods. Figure 1 contains different parts of the RSFJ and the whole assembled joint.

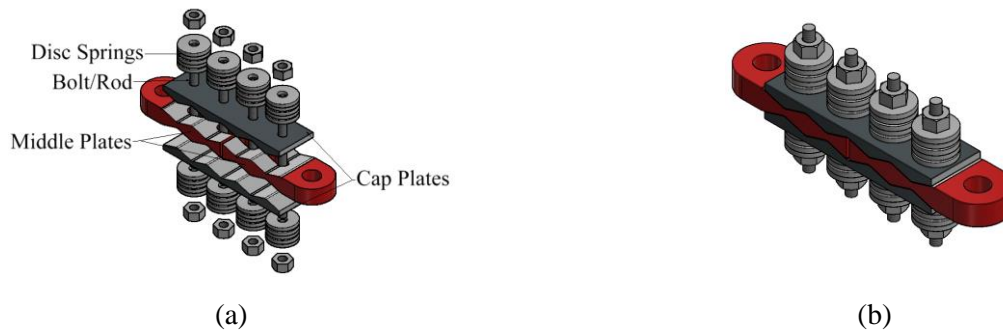


Figure 1: (a) Components of the RSFJ, (b) RSFJ assembly

After assembly, the bolts/rods are pre-stressed up to a desired designed level. This pre-stressing adds the self-centring characteristic while the energy dissipation is guaranteed through friction mechanism between the sliding grooved plates. The flag-shape performance of the joint has been observed in component level tests (Hashemi et al. 2017b) and the governing equations have been derived through past studies (Hashemi et al. 2016). On the system level, the RSFJ has been tested as hold-downs in rocking Cross Laminated Timber (CLT) shear wall as shown in Figure 2 under quasi-static loading (Hashemi et al. 2017a).

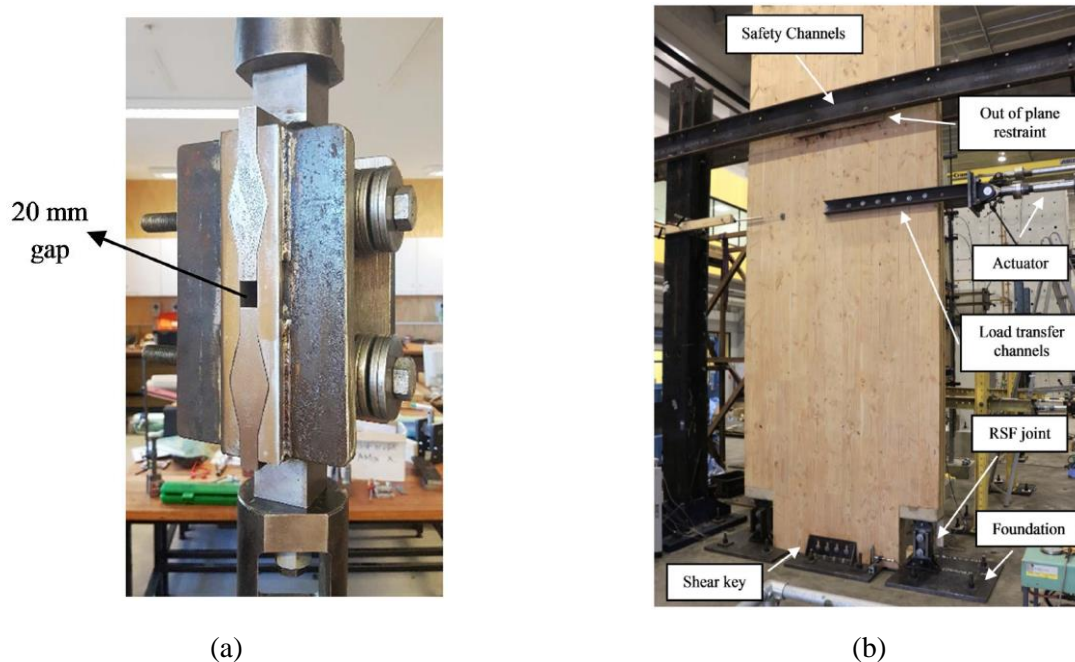


Figure 2: Experimental testing of rocking CLT walls with the RSFJ: (a) joint test, (b) wall test (Hashemi, Zarnani, et al. 2017a)

This concept has recently been extended to concrete shear walls (M. Darani et al. 2018), steel and timber braces (tension/compression) (Yousef-beik et al. 2018), steel MRF (Hashemi et al. 2018), coupled shear walls (Hashemi et al. 2017b), and secondary structures. Beside these applications, in- and out-of-plane rotational performance of the joint and a structural design guide for structures reinforced with the RSFJ have been investigated respectively by (Zarnani et al. 2018) and (Hashemi et al. 2018). In the following sections, the tension-only brace application of the joint has been explained in detail and the experimental tests and relevant results are reported.

3 TENSION-ONLY BRACE

The RSFJ can offer a flag-shape behaviour in tension and in compression. Where a compression displacement is required, an initial gap between the two middle plates is included. In that case, the stability analysis of the joint is of importance to prevent the global buckling (Yousef-beik et al. 2018). In the RSFJ tension-only brace, a tension member such as rods, plates or Reidbars can be used for the brace body and based on the force demand required, the number of rods/plates/Reidbars can be adjusted. Also, based on the drift requirement, the RSFJs can be used on only one end of the cross braces or on the two ends. In the latter case, since the two joints are tuned and tested to achieve the expected flag-shape behaviour before being used in the frame, they will slip simultaneously; however a tolerance of 10% in slipping force is suggested to be considered in the design phase which will increase the system over-strength accordingly. As the braced frame is loaded, one of the diagonal braces elongates while the other one shortens. The deformation in tension is provided initially by the elastic behaviour of the system and then is provided by the RSFJ after slip. On the compression side, respecting the details displayed in Figure 3, as the rods shorten, they are released and extend over the joint lateral surfaces. Therefore, there will be no compression force on the rods and RSFJs. In the reverse loading direction, a similar behaviour is expected; so, in a full cycle no member yield or buckle and there will be no pinching or slackness in the system. Hence, compared to conventional tension-only braces, not only is this one seismically reliable but also it can be considered as low-damage solution for new construction and retrofitting purposes. Also, as the diagonals are not designed for buckling, the section sizes will decrease significantly which makes the design and installation more convenient. In this system, the rods should be pre-stressed in order to remove their sagging due to the gravity load and to have a non-pinching behaviour. The level of this pre-stressing force is dependent on the frame geometry and the rods size. This force may delay the releasing process of the rods undergoing contraction. As will be shown later in the tests conducted, despite this pre-stressing force, the diagonal rods will still be released under contraction.

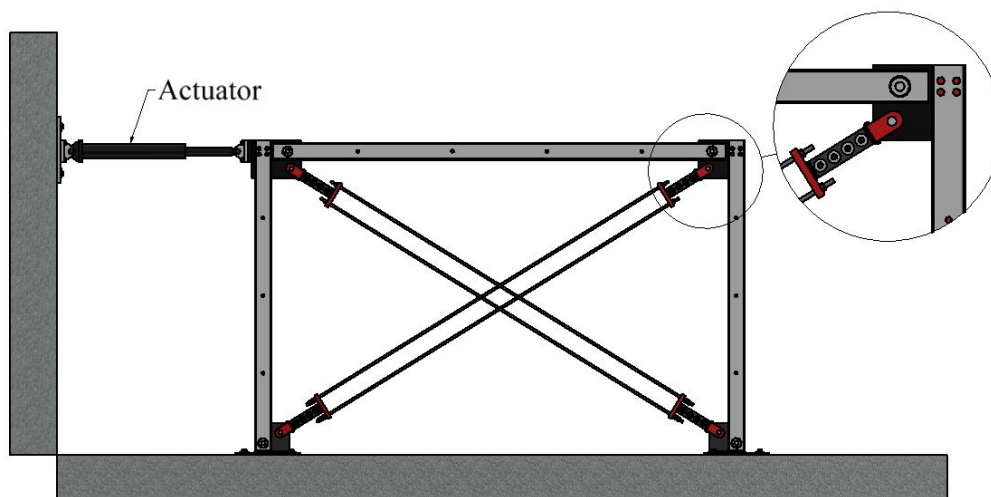


Figure 3: RSFJ tension-only brace and corresponding connections detail

4 TEST PROGRAM

4.1 Loading protocols

The ultimate goal of any loading regime is to qualify the performance of the intended member in real application. In this study, two types of loading protocols which have been employed for self-centring braces (Erochko et al. 2014a), are used. One of them is the loading protocol suggested by AISC 341 (AISC 341-10 2010) for static cyclic test in which it is stated that the brace should have twice the ductility capacity of the design story drift together with an accumulative inelastic axial ductility capacity of 200. In this regard, the following static loading protocol (see Figure 4(a)) in accordance with this standard is used for the tension-only RSFJ brace static test. The design level story drift is assumed to be 2.5%, which makes the MCE displacement equivalent to 5% drift.

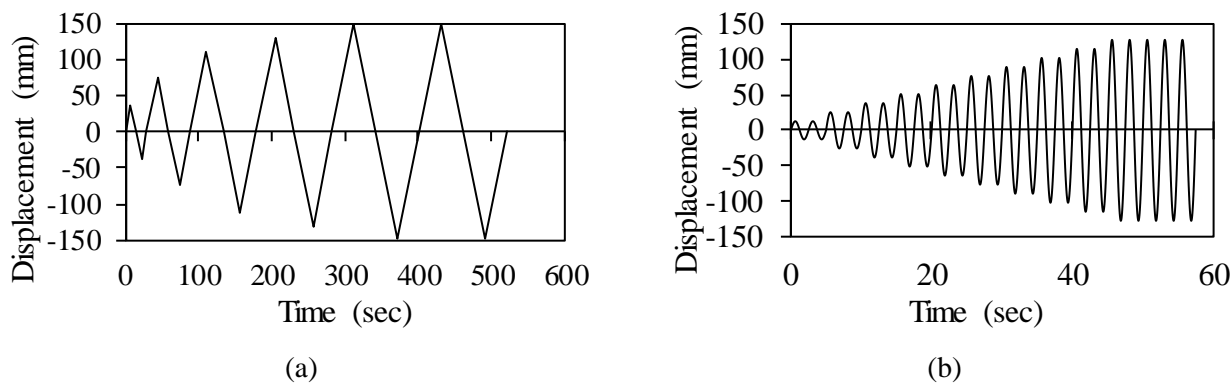


Figure 4: Loading protocols for the frame test: (a) static, (b) dynamic

For dynamic tests, according to ASCE 7 (ASCE/SEI 7-10 2010), each damper shall be tested with at least five fully reversed sinusoidal cycles with a period equivalent to the reduced building period after activation of the damper. In order to meet the requirements of AISC 341 as well, the dynamic loading protocol shown in Figure 4 (b) has been applied to the frame. This protocol is calibrated to match the maximum velocity capacity of the actuator used for this test, leading to constant frequency of 0.4 Hz at the maximum displacement of 120 mm in the final five cycles.

4.2 RSFJs design

RSFJs were designed based on the maximum force capacity of the actuator used and the loading protocols to demonstrate 5% drift ratio of the frame. In order to achieve this drift level, two RSFJ on each brace were considered. The design parameters of the joints are listed in Table 1.

Table 1: Design parameters of the RSFJs

Parameter	Description	Value
N_b	Number of bolts on each middle plate	2
N_d	Number of parallel discs per bolt per side	11
θ	Angle of grooves	17°

Detailed drawings of the corresponding designed middle and cap plates for the test are displayed in Figure 5. The slotted holes on the middle plates are elongated on just one side of the clamping rods since the joints will work in tension only.

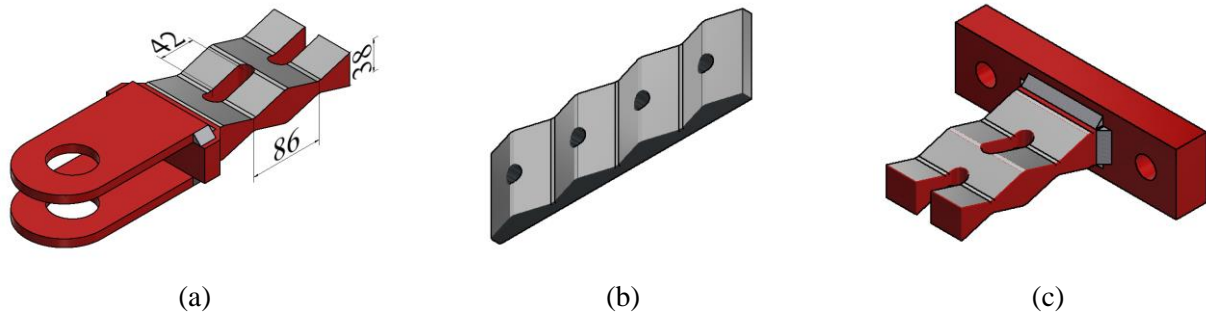


Figure 5: Detailed drawings of designed (a) middle plate towards the gusset plate, (b) cap plate, and (c) middle plate towards the diagonal rods (dimensions in mm)

4.3 Frame design

A two dimensional full-scale simple steel frame with dimensions of 5 m long and 3.1 m high was designed based on AS/NZS 1170 (2002), and NZS 3404 (1997) to satisfy different loading protocols planned to be applied and the force capacity of the actuator (300 kN). Pinned connections were considered for all of the members including the column base, the beam to column and the brace to gusset so that all members work axially. The beam and columns sections are back-to-back 180×75 PFC with 25 mm gap in between, the diameter of all pins is 50 mm and the gusset thickness is 25 mm. The brace bodies are two M24 8.8 rods. In order to prevent the individual members buckling, combination of timber spacers and bolts have been used between the back to back members in the beam and columns (with an even spacing). Furthermore, in order to minimize the lateral vibration during the dynamic testing and to keep the frame in-plan, a protection frame including four columns, two beams and four props were used in which the beams (as guiding elements) were located 6 mm apart from the main frame on each side. The whole test set-up including the main frame and the protection frame is shown in Figure 6.



Figure 6: Full test setup including the main and protection frames

5 TEST RESULTS

5.1 Joint component testing

Firstly, the joints were tested individually to confirm their desired performance before moving on to the frame test. The relative displacement between the two middle plates was measured by a Linear Variable differential Transformer (LVDT) and the force on the joint was measured by the load cell of the actuator. Joints were loaded up to 60 mm as per their design for three full cycles to demonstrate repeatability. Figure 7 shows one of the joints test result and compares it with the estimation. The reason for slight non-linear jump at the top-right corner of the recorded flag-shape is the non-linear behaviour of the disc springs as they are close to be fully flattened. This either needs to be considered in the design of the joints and other members or the disc springs displacement capacity should be restricted to their linear behaviour portion to predict the expected response. Note that all four joints were tested and their responses were quite matching.

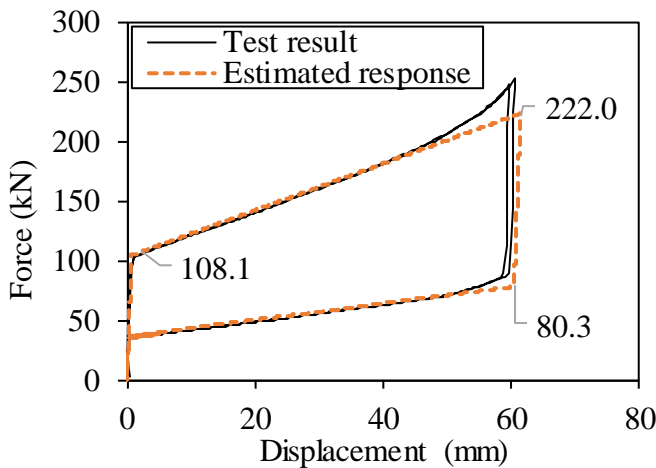


Figure 7: Comparison of the joint component test result and the estimated response

5.2 Frame quasi-static testing

After installation of the four tested joints on the frame, the diagonal braces were tightened and the loading protocol shown in Figure 4 (a) was applied to the frame. For the purpose of data acquisition, four LVDTs to measure deformation of the four joints, two draw wires on the column of the main frame to record the in-plane lateral deflection of that and the actuator load cell to measure the force on top of the frame were used. The corresponding frame response is shown in Figure 8.

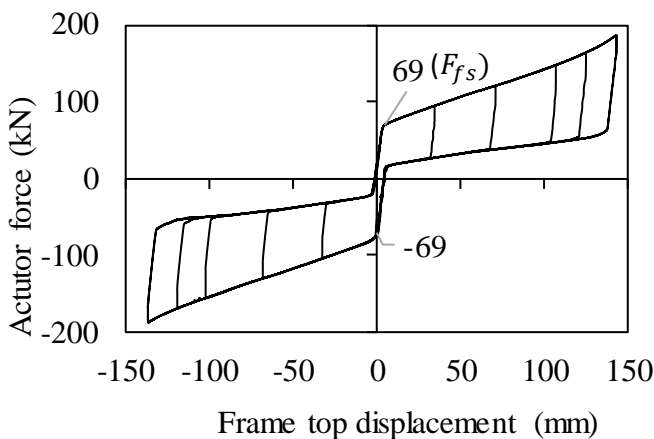


Figure 8: Frame response to quasi-static loading regime

Ignoring the tightening effects, one can use the following equations to obtain the frame parameters from the joint component testing data:

$$F_{frame} = F_{RSFJ} \times \cos \alpha \quad (1)$$

$$\Delta_{frame} = \frac{2\Delta_{RSFJ} + \Delta_{rods}}{\cos \alpha} \quad (2)$$

Where F_{frame} and Δ_{frame} are the horizontal in-plane force and displacement on top of the frame, F_{RSFJ} and Δ_{RSFJ} are the force and deformation response of the joints from component testing, and α is the acute angle between brace direction and horizon. As per Equation (1), the initial estimation of the frame slip force, F_{fs} , is 93.5 kN, however, the observation is 69 kN based on Figure 8. This difference stands for the pre-stressing effects on reducing the F_{fs} . According to the test result, the performance of the system is fully repeatable flag-shape with admissible initial stiffness.

5.3 Frame dynamic testing

In the next step, the frame was tested under the loading protocol in Figure 4 (b) to demonstrate the performance of the system under dynamic loading. Figure 10 (a) displays the corresponding frame response. As can be observed from this figure, the F_{fs} has increased when compared to the static test results showing existence of dynamic effects on the performance of the frame. In order to minimize these effects, die springs with capacity of 9 kN were added to one end of the cross braces. The die springs were flattened as there was no external load on the frame and clearly when the inclusive diagonal was under tension force, while on the other diagonal with no tensile force on, they opened to approach their un-deformed shape. Figure 10 shows the flattened and un-deformed die springs. The dynamic response of the frame with die springs is depicted in Figure 9 (b). Comparing the frame dynamic results with and without die springs (Figure 9 (a) and (b)), one can find out the effect of the die springs in reducing the slipping force from 82.5 to 70.5 kN, on average. Based on the observation, the frame dynamic response was soundly repeatable and stable in different amplitudes and presenting self-centring and energy dissipation. Due to this behaviour, the system does not suffer pinching or slackness.

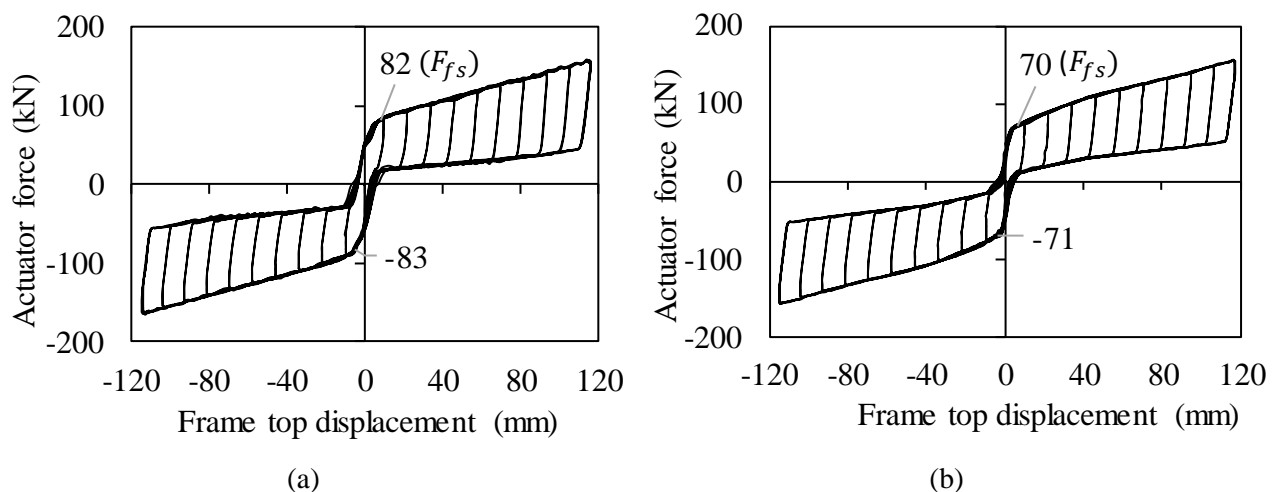
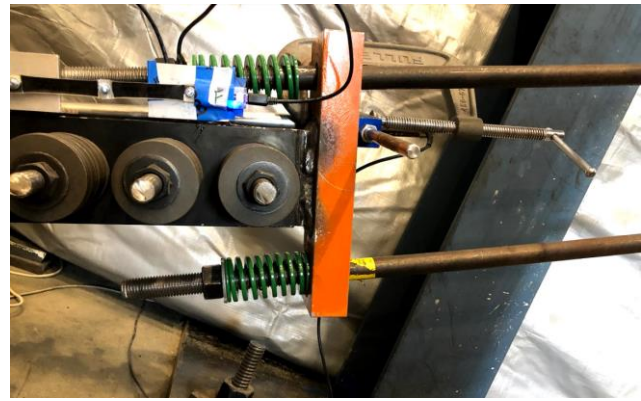


Figure 9: Frame response under dynamic loading protocol (a) without die springs, (b) with die springs



(a)



(b)

Figure 10: die springs (a) flattened (tensile force on the brace), (b) un-deformed (no force on the brace)

6 CONCLUSIONS

In this study, a new resilient tension-only brace has been introduced and experimentally tested where Resilient Slip Friction Joints (RSFJs) are attached to the tension-only diagonal braces to provide the required ductility and damping for the system. This bracing system can easily be installed on either new or existing structures to meet the low-damage design criteria so that the structure will remain operational after the event since the risk of structural repairs is remarkably reduced. The performance of the RSFJ has been experimentally verified on the component level and then quasi-static and dynamic full-scale experimental tests have been conducted to investigate the seismic performance of the RSFJ tension-only braces. According to the experimental results, the introduced braced system can offer fully repeatable flag-shape behaviour, against different loading regimes with no pinching and slackness up to MCE level. In sum, the findings of this research show the great potential of the proposed system for making new and existing buildings earthquake resistant.

7 ACKNOWLEDGEMENT

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