Seismic retrofitting of RC-frames using Resilient Slip Friction Joint Toggle-bracing system

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ABSTRACT

Seismic retrofitting of the current non-ductile or limited ductile RC buildings is one of the challenging design topics among the scholars and engineers. The common technique for RC-frame retrofitting involves adding conventional or dissipative yielding braces such as BRBs to the system. Through these additional braces, the overall stiffness and strength of the frame increase. By yielding of these braces prior to excessive plastic deformations in the RC-frames a portion of the seismic energy would be absorbed, resulting in limiting the overall drift and alleviating the damage on the main RC frame. This paper introduces an alternative method for retrofitting of RC-frames, using Toggle-Bracing system, equipped with self-centering damage-free Resilient Slip Friction Joints (RSFJs). The RSFJ-Toggle bracing can limit the story drift for the frame and increases the overall strength and stiffness of the system, while magnifying the small floor displacement for the joint to dissipate the seismic energy. It can also provide restoring force for the frame, in case of extreme seismic events. In this paper, firstly, the results of the RSFJs component testing are presented. Secondly, the performance of the RSFJ-brace assembly is studied through hysteresis performance of a numerical model of a RC-frame with and without RSFJ-Toggle bracing system. Finally, the recommendation for brace to RC frame connections are briefly provided, as well as stability considerations to prevent buckling of the brace system.

1 INTRODUCTION

Many existing structures that are vulnerable to seismic event are still in use in active seismic regions all over the world. In particular, Reinforce Concrete (RC) frames, designed without earthquake-resistant detailing requirements (pre-code frames) or following old structural codes cannot provide ductile behaviour and suffer from a number of following deficiencies (Pampanin et al. 2006, Opabola and Elwood 2018, Opabola et al. 2019):

- Insufficient reinforcement details (longitudinal or transverse) in beams, columns, or joints.
- Inadequate anchorage detailing for both longitudinal and transverse reinforcements.
- Lapped splices of column reinforcement just above the floor level
- Lower quality of material, such as plain round bars (smooth reinforcement) which can separate from concrete in severe earthquakes, due to Poisson effects.

As compared to steel MRFs, RC frames are stiffer (Wu et al. 2017), and the irreversible damage to the RC frames initiate at their plastic deformation which is around 1% story drift (Qu et al. 2015). In resolving such seismic deficiency of non-ductile, or limited ductile RC frames, various seismic retrofitting techniques have been introduced by researchers, to save the RC frame from seismic damages. Figure 1, proposed by (Kam et al. 2010), demonstrates various retrofitting options within Acceleration-Displacement Response Spectrum (ADRS) domain. As can be noted, different methods of retrofitting include local or global strengthening (e.g. adding shear wall or braces), added damping to the system, using base isolation and damping systems, and selective weakening (to improve frame ductility).

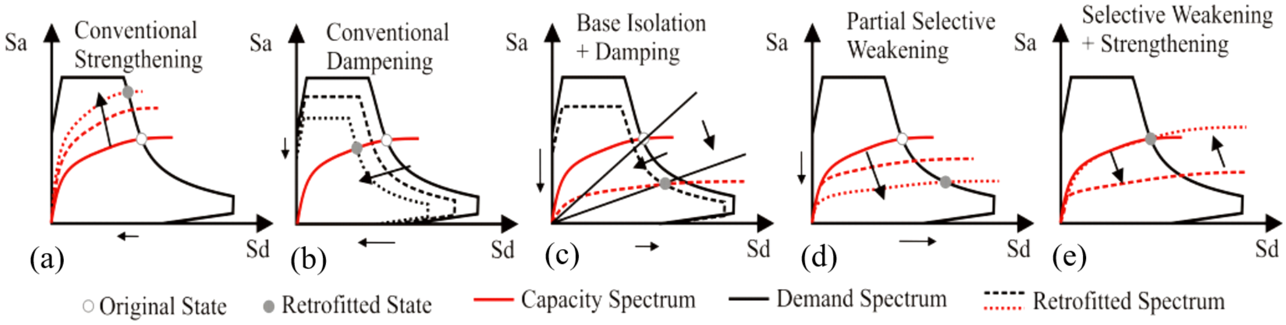

Figure 1: ADRS illustration of different retrofit strategies: strengthening, added damping, base isolation, weakening only, and Selective Weakening + Strengthening (Kam et al. 2010)

While choosing the most suited retrofitting strategy depends on various factors such as frame's structural characteristics, available gap between adjacent buildings, time, budget, permissible levels of implementing invasive methods and so on, the most common solutions are the addition of shear walls or steel braces (conventional or dissipative yielding braces such as BRBs) (Mahrenholtz et al. 2015). As compared to the traditional addition of shear wall which is a wet-retrofitting method, steel bracing can offer a number of advantages such as its comparatively lower weight and capability for pre-fabrication. Such additional braces are designed to yield prior to excessive plastic deformations in RC-frames, and absorb a portion of the seismic energy, alleviate the damage on the main RC frame and limit the overall drift of the system. As an alternative solution, damage-free dampers with bracings can also be utilized to dissipate the seismic energy without any buckling or yielding of the material. As for the displacement-based dampers, it is worth noting that the efficiency of such systems relies on the sufficient damper displacement, which could be limited for stiff non-ductile systems with limited drift capacity. To increase the efficiency of proposed system, the damper deflection can be magnified via toggle-bracing configuration.

This paper introduces a new alternative method for retrofitting of RC-frames, using Toggle-Bracing system, equipped with self-centering damage-free Resilient Slip Friction Joints (RSFJs). The RSFJ-Toggle bracing can limit the story drift for the frame and increases the overall strength and stiffness of the system, while magnifying the small floor displacement for the joint to dissipate the seismic energy, thus it performs as combination of category ***a*** and ***b*** in figure 1. It can also provide restoring force for the frame, in case of extreme seismic events. In this paper, the performance of the RSFJ is briefly investigated and validated through experimental testing. Then, the RSFJ-Toggle bracing system is explained through numerical modelling. Finally, the requirements of brace to RC frame connections are briefly provided as well.

2 RSFJ COMPONENT TESTING

RSFJ is a self-centering friction energy dissipating joint invented by (Zarnani and Quenneville 2015), capable of being utilized in concrete, steel, timber or hybrid structures. As depicted in the figure 2, the joint consists of especially grooved cap and middle plates, clamped by high strength bolts and pre-stressed disk springs. Energy is dissipated by frictional sliding of the middle plates, while the specific shapes of the ridges combined by stack of pre-stressed disk springs provides the self-centering force. The governing force-deflection equations for the joint which have been derived through past studies (Hashemi et al. 2017b), can provide a tuneable symmetric flag-shape behaviour, both in tension and compression. For more info, regarding the applications of the joint, it can be referred to (Bagheri et al. 2020, Hashemi et al. 2017a, Yousefbeik et al. 2020).

Figure 3-a shows the testing of a joint component, using Universal Testing Machine. The groove angle was designed to be 21° with nearly equal static and kinetic coefficient of friction, $\mu s \approx \mu k = 0.13$, due to using grease lubrication (Veismoradi et al. 2019). A stack of 14 disk spring with ultimate force and deflection capacity of 132kN and 1.75mm were used on each side of the joint, using pre-stressing force of $F_{b,pre}$=66kN. The designed deflection capacity of the joint was 50mm, with the F_{slip} and F_{ult} equal to 71 and 142kN, respectively. The comparison between analytical flag-shape and experimental outcomes are provided in Figure 3-b, as well.

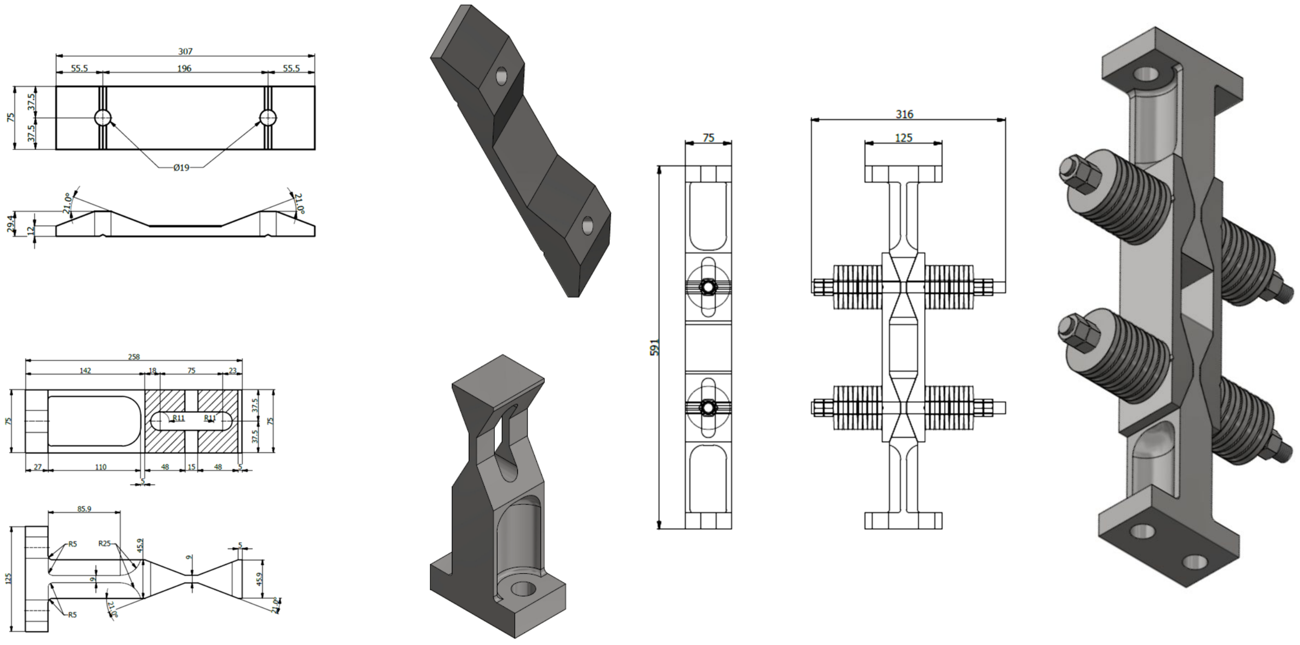

Figure 2: Detailed drawings of tested RSFJ joint

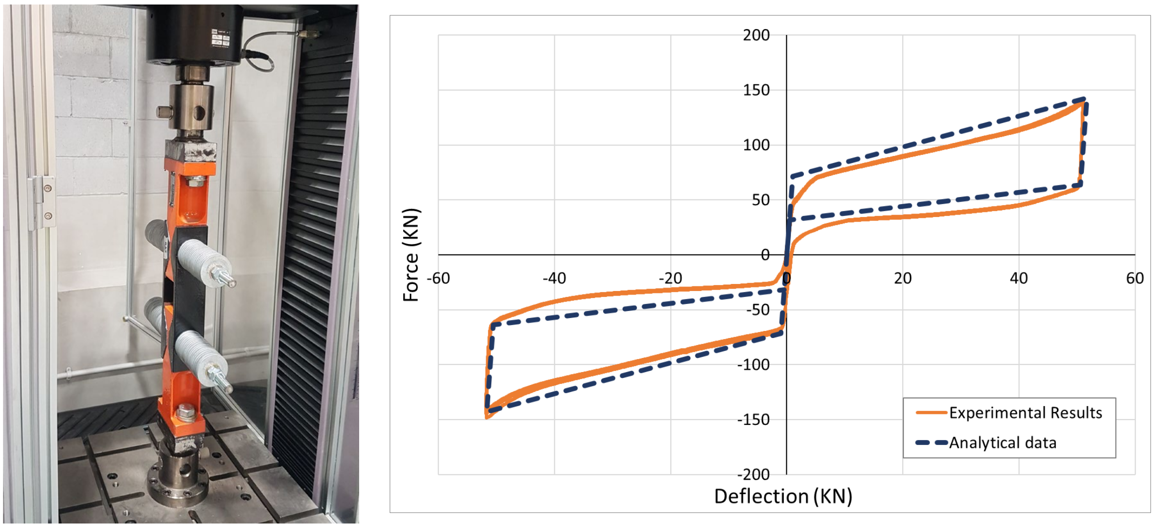

Figure 3:Comparison of the joint component test result and the estimated response

3 RSFJ-TOGGLE BRACING SYSTEM

3.1 RSFJ-Toggle brace arrangements

RSFJ is classified as displacement-dependent devices and thus, its performance depends on the relative displacement of its two ends. While many possibilities can be considered for connecting the joint to the structure, the key locations is where the expected relative displacements are highest for the device. As for the non-seismically designed RC frame where the maximum permissible drift of the frame is in the range of 1% or less, common installation of the joint such as diagonal and chevron cannot provide considerable relative displacement for the joint to dissipate the seismic energy. To tackle this issue, Toggle-bracing arrangement can be employed to amplify the small deflection of the frame into a large relative motion for the joint. The concept was introduced by Taylor on viscous dampers and its effectiveness was verified through shaking table tests (Taylor 2000). Figure 4 depicts the different arrangements of toggle bracing systems introduced by previous studies, as comparison to diagonal and chevron bracing system, while the amplification factor (f) for each system is provided in the table 1 (Constantinou et al. 2001, Hwang et al. 2005). The following relationships exists for the installation of the joint in the system:

$$u_d = f \times u \tag{1}$$

$$F = f \times F_d \tag{2}$$

Where u_d, and F_d are the relative displacement and force along the axis of the joint. The parameters u and F denote the story displacement and horizontal component of the force exerted to the frame. Among the available arrangements, the lower toggle (Type II) was adopted here for analytical investigation, which connect the toggle brace system to the three beam/column joints of the frame. For other arrangements, one may utilize the appropriate amplification factor equation to calculate the required joint deflection within the allowable frame drift. It should be noted that the braces are assumed to be pin-connected to the beam/column joints and the designed connections can fully transfer the brace forces to the RC frame.

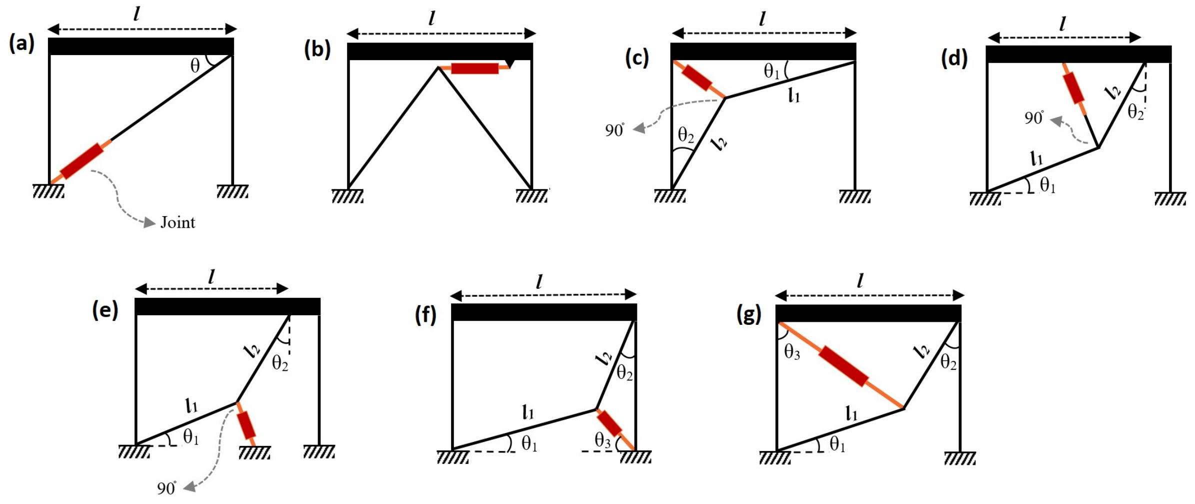

Figure 4: Schematic view of different toggle-bracings, as compared to common bracing systems

Table 1: Amplification factor for different bracing system

System ID	**a**	**b**	**c**
name	Diagonal	Chevron	Reverse Toggle
Amplification factor	$\cos\theta$	1.0	$\frac{\cos\theta_1}{\cos(\theta_1+\theta_2)} - \cos\theta_2$
d	**e**	**f**	**g**
Upper Toggle (type I)	Lower Toggle (type I)	Lower Toggle (type II)	Upper Toggle (type II)
$\frac{\sin\theta_2}{\cos(\theta_1+\theta_2)} + \sin\theta_1$	$\frac{\sin\theta_2}{\cos(\theta_1+\theta_2)}$	$\frac{\sin\theta_2 \sin(\theta_1+\theta_3)}{\cos(\theta_1+\theta_2)}$	$\frac{\sin\theta_2}{\cos(\theta_1+\theta_2)}\cos(\theta_3-\theta_1) + \sin\theta_3$

3.2 Numerical modelling

A single bay of non-ductile RC frame, based on experimental works of (Al-Sadoon 2016) was selected to investigate the performance of the RSFJ-Toggle brace system. The selected frame (Figure 5) represents the exterior ground floor level frame of a 6-story RC frame, designed based on 1965 NBCC. Figure 6 shows the obtained cyclic performance of the tested frame, which clearly indicates its rapid strength degradation and brittle behaviour. The same frame was modelled in SAP2000 and its nonlinearity was considered via fibre hinges at both ends of columns and beams. The comparison between pushover analyses with experimental cyclic performance of the frame shows good agreement and highlights the elastic performance of the frame when the lateral drift is below 40mm (≈1% frame drift). An RSFJ-Toggle brace system with lower Toggle type II arrangement (Figure 4-f) was assumed for retrofit of the RC frame (θ_1=29.6, θ_2=36.6, θ_3=40.0), with amplification factor of 1.4. It is worth noting that the amplification factor for each toggle bracing arrangement is derived from theoretical equations that usually neglects the axial braces' deformation. Therefore, the actual joint deformation is expected to be marginally less than theoretical u_d, which can be modified after finalizing the brace design. Figure 7-a shows the utilized RSFJ for the modelled toggle-bracing configuration, based on the target drift of the frame (36mm ≈ 1% drift), while the cyclic pushover curve for the frame is depicted in Figure 7-b, for comparison. As can be noted, the damping of the system, as well as its initial stiffness is increased. It should be pinpointed that the maximum base shear in the pull and push direction differs, which is due to the fact that the magnification factor can change with loading direction (Zhang et al. 2012). Such behaviour depends on the geometrical configuration of the system, as well as targeted drift. If the differences the performance of the system is sensible in the push or pull direction, then the effect should be either considered in the retrofit strategy, or addressed by implementing toggle braces in two bays.

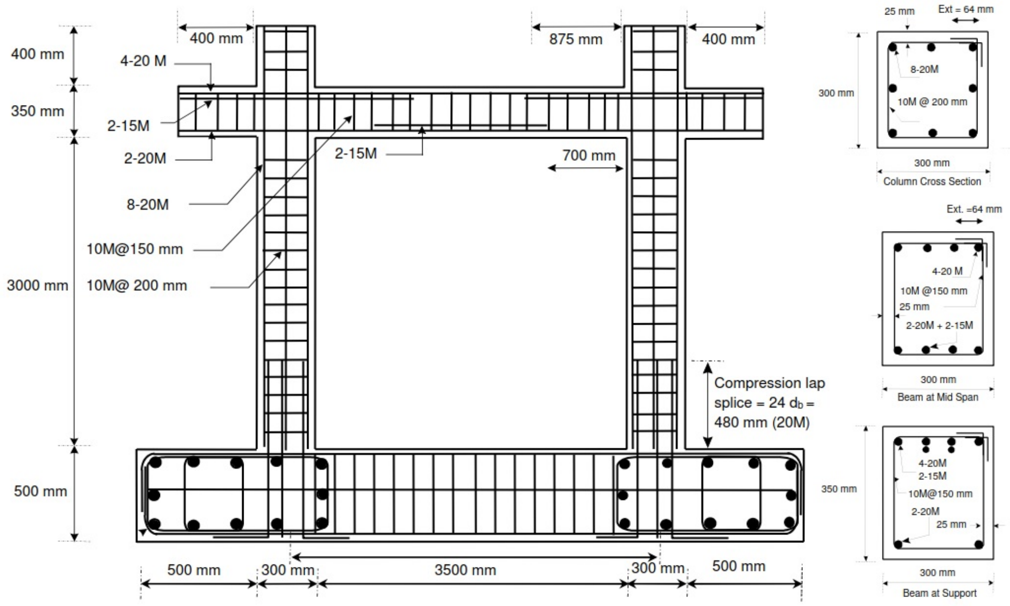

Figure 5: Section and reinforcement detail of the tested frame (Al-Sadoon 2016)

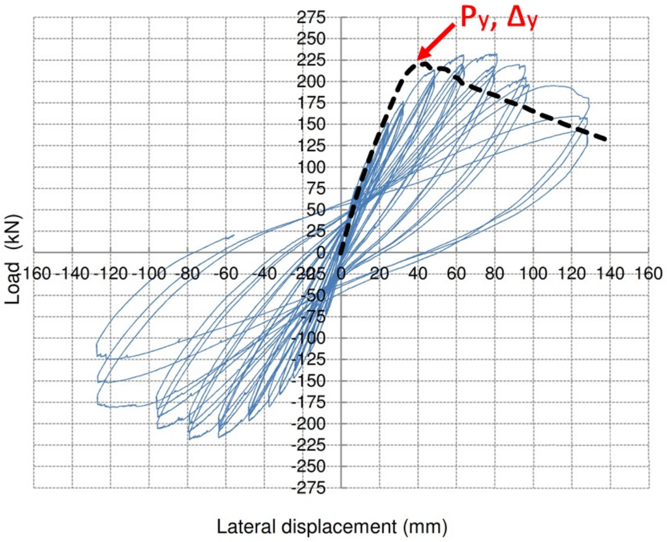

Figure 6: Comparison of the pushover results with the experimental hysteretic load displacement of the frame (Al-Sadoon 2016)

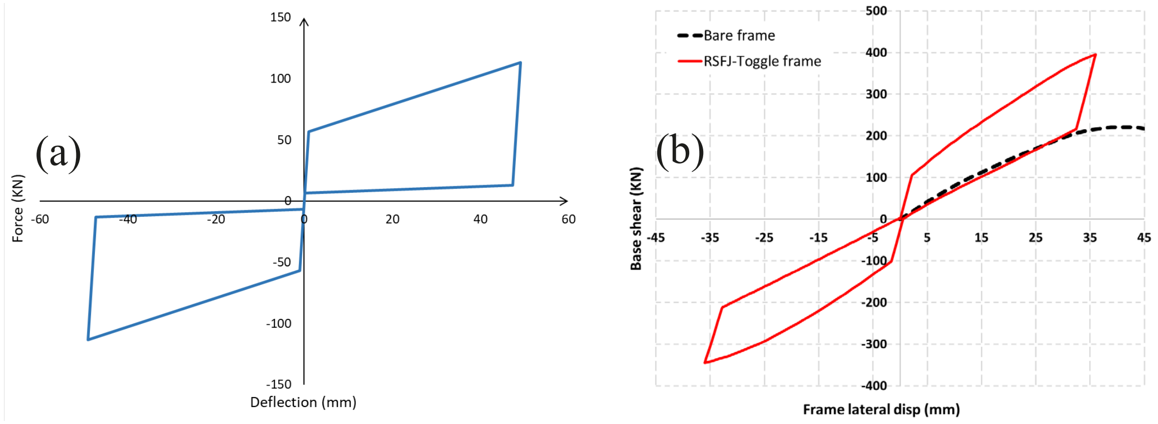

Figure 7: (Left) Flag-shape behaviour of the Utilized RSFJ in the toggle-brace system (F_{slip}=56.6, F_{ult}=113.1, $F_{restoring}$=12.9, F_{res}=6.4, μ=0.18, and Deflection capacity=49.1mm); and (Right) Cyclic pushover of the retrofitted frame up to 36mm lateral displacement

4 BRACE TO RC FRAME CONNECTION CONSIDERATIONS

Similar to BRB retrofitting, the RSFJ-Toggle bracing can be fitted within a continuous steel frame to be attached to the RC-frame via post-installed anchors. While such a configuration is relatively expensive and complicated, it can distribute the toggle bracing forces into the RC frame, in a more uniform manner. Sufficient number of anchorages are required to ensure that the ultimate capacity of the system is not limited by anchor failure modes (Figure 8). To check the capacity of anchorages, it can be referred to (ACI 349-13 2013).

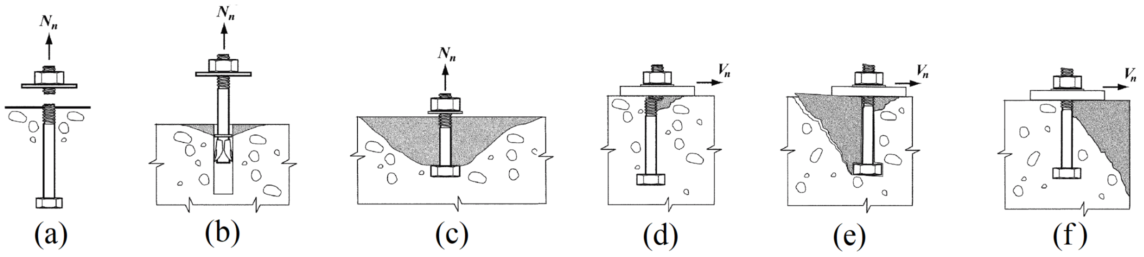

Figure 8: Anchor failure modes: (a) tensile rupture, (b) pull out in tension, (c) bond failure, (d) shear failure, (e) pry out failure, and (f) concrete breakout (ACI 349-13 2013)

Other options would be to directly install the toggle-bracing system to the RC-frame. The efficiency of such system depends on the ability of the connection between RC frame and bracing member to successfully transfer the load. A number of studies investigated the connection performance of RC-frames with steel braces using Uniform Force Method (Thornton 1984) (see for example, Maheri and Yazdani 2016). The similar procedure which is common for the design of gusset plates in steel frame construction, could be utilized for the RC gusset plate connection with an extra steps and considerations, such as designing the gusset-to-anchor bracket plates and the stud rods connecting these plates to the concrete member. Figure 9 shows the schematic view of the connection and the loads applied to the gusset plate. It is worth noting that such connection might relocate the formation of plastic hinges outside of beam/column joint region and increase its strength and stiffness. The brace to gusset connection can be selected as fully pinned, to exclude the effects of in-plane moments from brace to gusset. The normal component force forces (V_b and H_c) are transferred to the concrete through the stud bars, while tangential force can be transferred through friction force capacity between concrete and steel plate. A value of μ=0.4 can be selected with confidence, for the friction coefficient between concrete and steel frame, based on the works of (Rabbat and Russell 1985, Baltay and Gjelsvik 1990, Qu et al. 2015). If the brace tangential component force surpasses the friction capacity, additional shear keys or shear stud bars might be needed to compensate the difference.

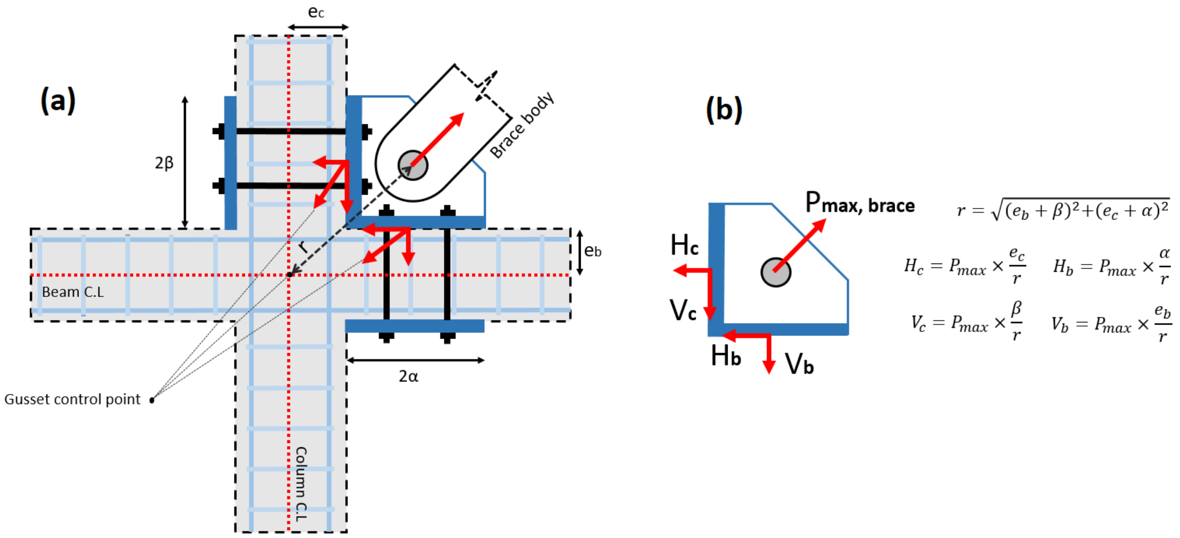

Figure 9:The schematic view of the connection suggested for retrofitting of RC frame with RSFJ-Toggle brace, and (b) free-body diagram of the gusset plate with required equation for UFM method (Thornton 1984)

Another point regarding the design of gusset plates for RSFJ-Toggle bracing systems is the buckling of gusset plates. Unlike ordinary braced frames, where braces are expected to buckle for energy dissipation and gusset plates are designed for allowing this out-of-plane rotation, the RSFJ-Toggle bracing system dissipate the energy through joint component sliding and thus, the gusset plate must not deform out-of-plane and should keep the braces in-plane during earthquake. A number of methods have been introduced and explained by researchers to minimize the gusset plate out-of-plane buckling, which can be utilized for improving the design of the gusset plate:

- Using stiffeners on the gusset plate edges
- Using effective length factor of 2.0 for designing the gusset plates (Mahrenholtz et al. 2015)
- Designing the gusset plate for a lateral force equal to 2.5% of the brace ultimate compressive load, based NZS3404 code (Clause 6.7.2) and works of (MacRae and Clifton 2015).

While the studies of (Lee 2002, Lin, Tsai et al. 2014) suggest that the gusset plate should sustain both axial force from brace and secondary loading due to frame action effects, the latter is not explicitly considered in most design methods. The results of (Mahrenholtz, Lin et al. 2015, Westeneng 2016) showed that in their cases, frame action effect contributed about 8~10% of the total force demand. For the sake of simplifying the design procedure, one can increase the tangential force for the gusset plate design (1.1*H_b and 1.1*V_c) and update the welding details, number of stud bars and so on to roughly include the effect of frame actions; or utilize the suggested equivalent strut model (Lee 2002, Lin, Tsai et al. 2014) in order to more accurately calculate the resulting force from frame action effects.

5 STABILITY CONSIDERATION

Though promising performance of the proposed bracing systems, there are some possible buckling modes that may disrupt the performance of the brace. The first one that must be avoided is the buckling of the utilized friction joint. Due to inherent geometrical characteristics of the RSFJ, it has a rotational flexibility in in-plane and out-of-plane direction, which might lead to buckling of the joint, if not properly designed. This rotational flexibility is depicted in the Figure 10.

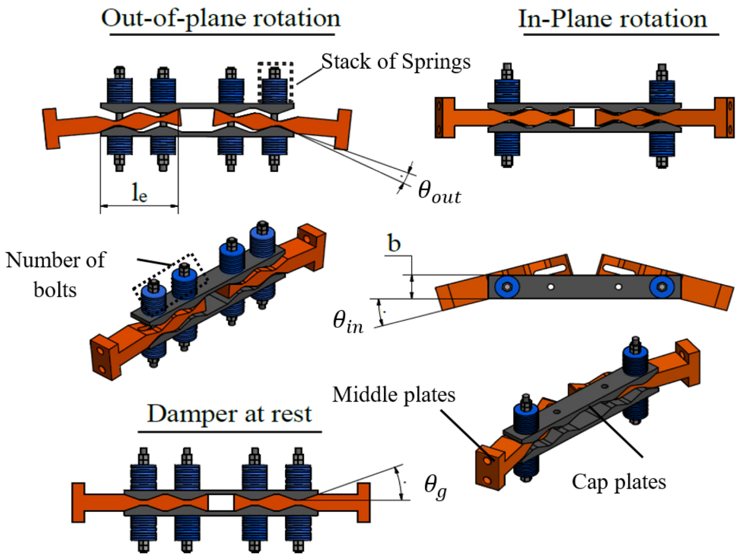

Figure 10: the deformed shape of RSFJ: out-of-plane, and in-plane

As a result of these rotational flexibilities, RSFJ is susceptible to buckle in the out-of-plane and in-plane direction. As for the case where an extension body is attached, the stability of the joint-brace assembly should be considered. Figure 11 shows the mentioned two buckling modes. It should be noted that additional mechanisms might be needed to increase the buckling load of the joint and/or joint brace assembly, if the joint (or joint-brace) buckling load is lower than the target design force of the system in the brace. This topic is still under investigation and requires further studies.

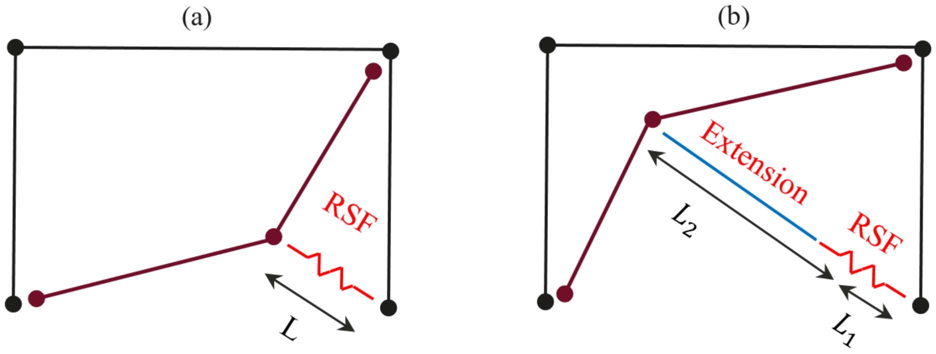

Figure 11: buckling modes of the Toggle-RSFJ bracing system: (a) buckling of the joint, and (b) buckling of the joint-brace assembly

6 CONCLUDING REMARKS

This paper introduced a new method for retrofitting of RC-frame, by utilizing self-centering damage-avoidant RSFJ in toggle-bracing configuration. The attached systems can increase the stiffness and damping of the RC-frame, without any damage or plastic deformation of the braces and provide self-centering, in case of extreme seismic event. In this paper, firstly, the results of the RSFJs component testing were presented and the performance of the RSFJ-brace assembly were investigated through cyclic pushover performance of a numerical model of a non-ductile RC-frame with RSFJ-Toggle bracing system. Finally, some of the recommendation for designing the RSFJ-toggle brace to RC frame connections are briefly provided, as well as its stability considerations. While the initial numerical investigations highlight the capability of the system for retrofitting of the RC-frame, large-scale experimental testing is planned to be performed on an RC-frame, in the near future to further investigate the performance of the system.

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