Experimental Testing of Brittle RC Frames Strengthened by RSFJ-toggle Bracing System

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ABSTRACT

This paper investigates the performance of a new retrofitting system, consisting of self-centring damper resilient slip friction joint (RSFJ)-toggle bracing system, as a global retrofitting method for deficient RC frame structures. The RSFJ-toggle bracing system can be activated within small drift values of the frame and preserve the frame from excessive damage. Two scaled deficient RC frames representing typical pre-1970s RC moment resisting frames were constructed and tested to investigate the performance of such a retrofitting system. Material testing of the concrete and steel rebars as well as the damper component testing were conducted to gain accurate data for numerical modelling. Recommendations regarding the proper design of various aspects of this retrofitting system are provided, including the brace buckling design, instability consideration for the damper, as well as the overall system, connection detailing and gusset plate design requirements. The experimental observations demonstrate the improved behaviour of the frame in terms of energy dissipation and enhanced stiffness and strength for the upgraded RC frame. As per the findings of this study, the proposed retrofit solution can strengthen the frames within a limited drift and improve the frame's damping with a repeatable semi-flag shape hysteresis performance.

1 INTRODUCTION

A reinforced Concrete (RC) building structure should have sufficient strength, stiffness and ductility to perform well during major seismic events. A high number of existing RC buildings, especially those built prior to 1970s might not satisfy the current seismic codes criteria, due to the fact that they are mainly designed based on gravity load only (O'Reilly et al. 2018), and lack the seismic detailing required for lateral loads and deformations imposed during high seismic events. The need for practical retrofitting techniques still remains an important topic within the structural engineering community.

Depending on the required level of seismic retrofitting, the deficient RC structures may go through a member-level upgrading (local-retrofitting), or structural-level upgrading (global-retrofitting)(Joseph, Mwafy et al. 2022). Besides utilizing traditional global retrofitting methods, researchers have also explored the possibility of using innovative seismic dampers for seismic upgrading of RC frames (Javidan and Kim 2019, Hashemi 2022).

This paper presents the experimental results obtained by the cyclic testing of a RC frame equipped with a self-centring friction damper named Resilient Slip friction Joint (RSFJ). The damper characteristics and performance behaviour has been investigated both in component and structural level (see for example, Hashemi et al. 2017, Yousef-beik et al. 2020, Veismoradi et al. 2021a, Veismoradi et al. 2021b, Yousef-beik, et al. 2021a). Here, the damper is attached in a toggle bracing arrangement to the structure. The initial numerical investigation for such system has been conducted in previous research(Veismoradi et al. 2020). Here, the experimental results are the main focus of this study. Two identical one-story single bay RC frames were tested for this purpose (one serves as a benchmark bare frame while the second frame represents a retrofitted performance). The paper also covers the criteria considered for the design of the retrofit scheme in this research. While the design recommendations and outcomes presented here are based on a self-centring flag-shaped damper, it can also be utilized for retrofit designing with other dampers as well.

2 DEFICIENT RC FRAME CONSIDERATIONS

Two small scale RC frame, similar to the frame studied by Al-Sadoon et al. (2020), were manufactured for the experimental testing. The frame specimens represent a well-constructed pre-1970s gravity-only RC moment resisting frame with no specific seismic provisions (Figure 1).

A few aspects were considered for the construction of these frames so they better represent an old-fashioned deficient RC frame. It is a possibility that old-fashioned RC frames were constructed with material and rebars that may not demonstrate the quality and characteristics of today's material and their characteristics are subject to change over time. For the retrofit purposes, the probable characteristics of materials should be considered for analysis. Here, a low value for compressive strength of the concrete was considered (approximately 20MPa) to better demonstrate a frame with low strength concrete.

Another aspect is the spacing between the adjacent rebars. For the manufactured frames, the middle longitudinal rebars are not restrained against buckling; moreover, the shear rebar distance s = 90mm is slightly bigger than the d/2 = 88.5mm = (220-25-10-8)/2. Another indicator suggested by Stirrat et al. (2014) is the ratio of concrete core to gross concrete area (A_c/A_g). They stated that for the column sections with the ratio of A_c/A_g less than 70% may suggest a non-ductile behaviour (for the current RC frame, this ratio is calculated as 64.7%).

As a final point, the structural deficiency of strong-beam weak-column is considered for the frames where the beam section of the frame is slightly larger; and the Sway index = 0.85 indicates a potential column sway mechanism. Moreover, it was noted that during the cyclic pushover testing of the RC bare frame, the concrete cracks were firstly and mostly developed in the columns which pinpoints the occurrence of column sway mechanism before the beam hinging.

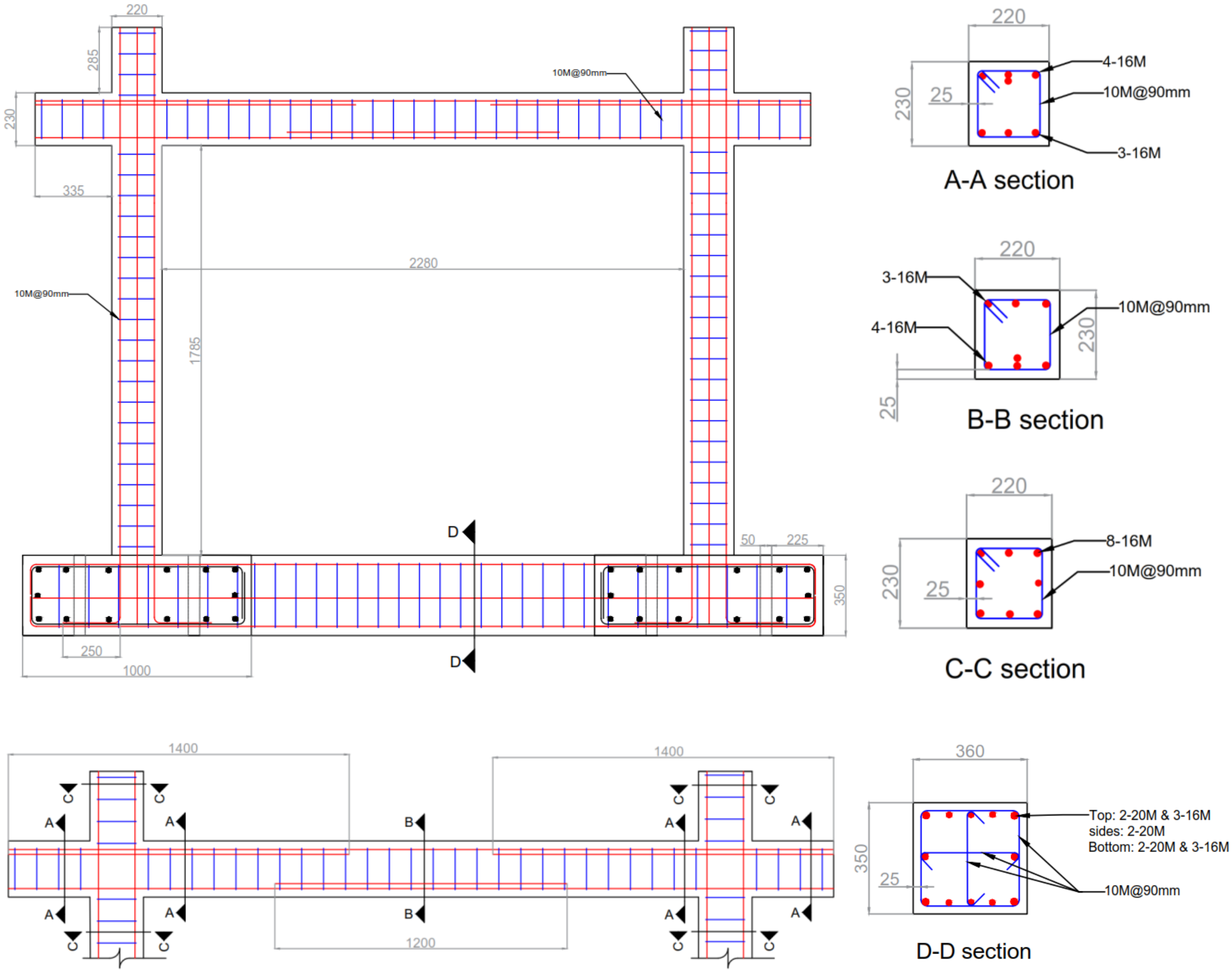


Figure 1: The RC frame rebar detailing and section geometry

3 RETROFIT DESIGN CONSIDERATIONS

3.1 Brace Design

Figure 2 shows the three brace members of the toggle-bracing system that are pin-connected to their intersection point. All three braces are SHS75x6.0; and the damper-brace contains a telescopic male and female circular tube section to prevent buckling. Sufficient distance L is available so that the damper can fully expand, otherwise the top and bottom forces would cancel each other when the frame drifts to the right (γ=180) and system interlocks. Neglecting the friction in the pin, the braces act in axial force and follow the Lami's Theorem:

$$\frac{F_{Top\ brace}}{sin\ \alpha} = \frac{F_{Bottom\ brace}}{sin\ \beta} = \frac{F_{damper}}{sin\ \gamma} \qquad (1)$$

The top and bottom brace axial forces can be derived from above equation and needs to have sufficient capacity to withstand the damper ultimate force without any buckling or yielding. For the very short distance L (γ ≈ 180), the small damper force would result in high top and bottom brace forces and thus uneconomical bigger sections for these two elements, while the bigger distance L would lead to smaller forces in the braces and might not justify using the toggle-bracing arrangement. For the current test setup (γ=154, β=115, α=92), the ultimate force of the damper-brace assembly was set to 48.8kN, thus the top and bottom braces need to be designed for 111.25kN and 100.9kN, respectively.

For a proper energy dissipation in the proposed bracing system, any possible buckling modes that may interrupt the performance of the braces need to be avoided. It has been shown that the compression strength of the RSFJ might drop due to its rotation flexibility (Yousef-beik et al. 2021b). Therefore, an Anti-Buckling Tube (ABT) is added to the damper-brace assembly to present a symmetric hysteresis behaviour, both in tension and compression. It is worth noting that the stability analysis of the RSFJ is based on the assumption that the damper-brace assembly has an effective length factor of K=1 (i.e. the damper-brace is pin-pin connected at both ends).

Contrary to regular braces where the brace is pin-connected to rigid ends, the braces in toggle bracing system (including RSFJ damper-brace) are connected to one rigid end and one restrained end as can be seen in Figure 2. The restrained point (i.e. the point where all three braces are pin-connected) can go out-of plane during damper-brace compression force, depending on the level of brace and connections' stiffness and the overall buckling capacity of the system.

An optimized design for the system needs to assume the sections of the braces and end support characteristics, and then calculate the buckling load for each brace and make sure that the ultimate compressive strength of the RSFJ-brace can be achieved before any of the other braces yield or buckle. The thorough buckling analysis of the RSFJ-toggle bracing system may require further analysis and is out of the scope of this paper. here, a conservative approach was taken to size the brace sections based on the effective length factor concept.

As can be noted, the braces can be assumed to be pin-pin connected for the in-plane behaviour and connected as fixed-free for the out-of-plane behaviour. The presence of the pin at the point A and the five cleats that are connected to this point and designed to remain elastic would make the rotation of point A negligible. However, for the sake of simplicity and having a margin of safety, the influence of node A rotational and translational stiffness was disregarded for the AB and AC braces, while considering a large rotational stiffness for the point B and C. Therefore, both braces can be designed based on effective length factor K=2.0 For the RSFJ-brace design, it can be stated that the effective length factor lies between an idealized pin-pin connection and the one with slight out-of-plane movement due to elastic out-of-plane movement of point A. Again, an effective length factor of 2 was considered for the RSFJ-brace (thus neglecting the present restraints in the middle point), to provide a margin of safety for the damper-brace assembly. It should be noted that in case of out-of-plane bending of the brace, it is unlikely that the damper experiences any damage and it would only decrease its deflection capacity (thanks to the out-of-plane flexibility of the RSFJ).

The final check regarding the stability of the toggle-bracing system is the buckling analysis of the damper-brace assembly itself. On this basis, the damper-brace was checked against stiffness deterioration path (the effects of P-δ and initial imperfection which inclines toward Euler buckling load as the lateral deformation increases) and strength deterioration path (the axial strength of the system when a plastic hinge develops in the brace body or the ABT). The ultimate force demand was below the Euler path and strength path which means the damper-brace would remain completely elastic up to its damper ultimate force.

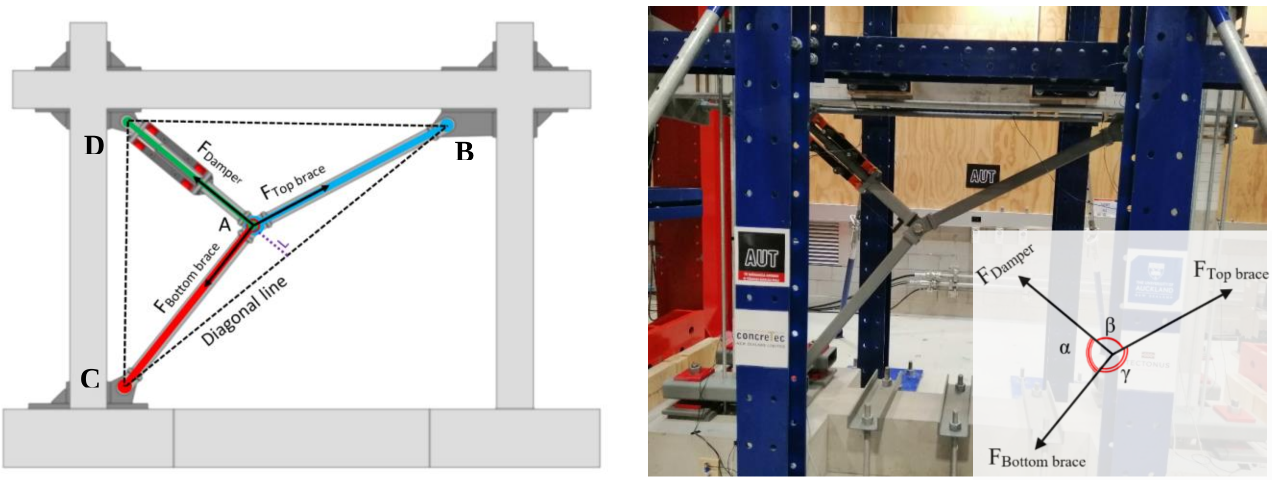


Figure 2: Parameter definition for the toggle brace forces

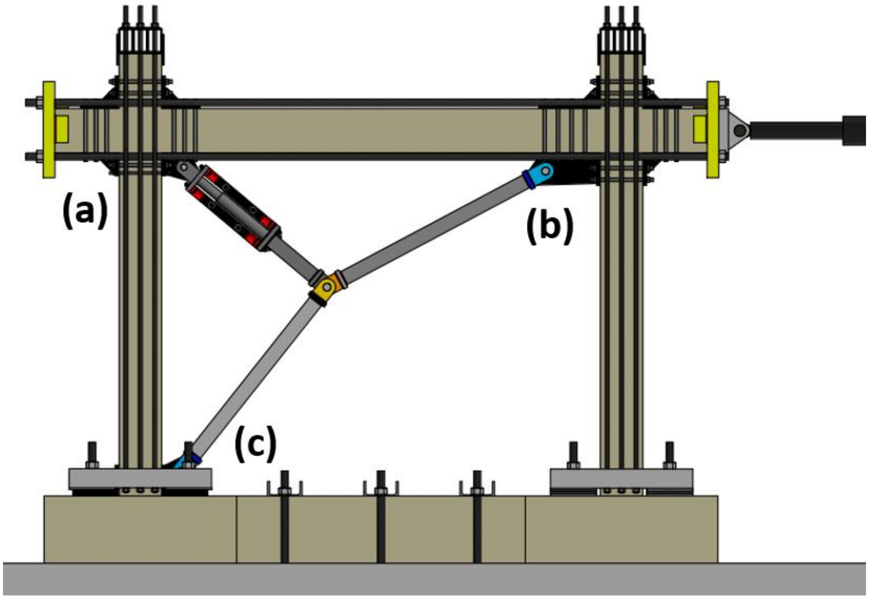
3.2 Connection design

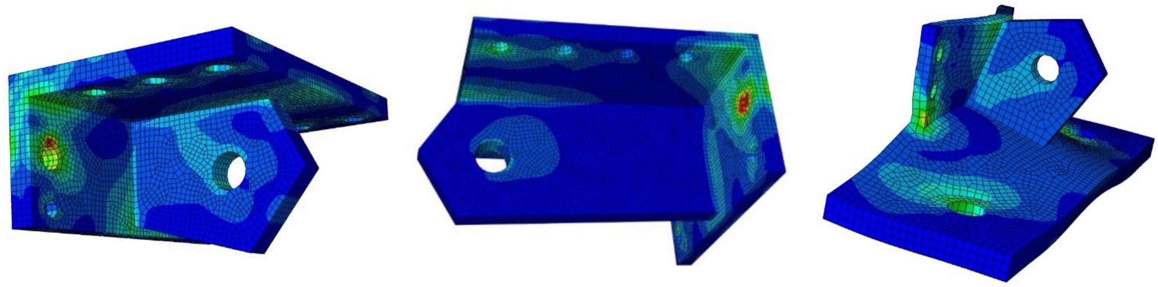
Two main methods for connecting the RSFJ-toggle bracing system to the RC frame can be considered, namely the direct connection and indirect connection. Regarding the indirect connection, the RSFJ-Toggle bracing retrofit can be assembled as a separate steel braced frame to be continuously attached to the side face of the RC-frame via post-installed anchors. In this way, the brace forces would go to the steel columns and beam. While such a configuration might seem relatively more expensive, it may appear as less challenging for engineers since it can be separately designed and then connected to the frame and collect the RC frame force in a more distributed manner and enable using larger brace section and damper. Other options would be to install the toggle-bracing system directly to the RC-frame, where the RC frame is connected to the braces at discrete locations (beam-column joints for this case). The efficiency of such system depends on the ability of the connection between RC frame and bracing members to successfully transfer the load. Moreover, the extra force from the braces to the RC columns and beam might change the failure mechanism on these elements, especially if the column contains high axial load (0.30* $P/A_g f'_c$). Considering the current RC frame's test with 0.15* $P/A_g f'_c$ (=440 kN for both columns), it was decided to employ indirect connection, where braces are directly connected to the RC frame.

Similar to any gusset plate design, the criteria considered for the design of gusset plate includes section yielding, net section fracture, shear tear out and compression design of the gusset, along with additional criteria to transfer the brace axial forces to the RC frame. The pinned connection for the braces minimizes the in-plane induced moment to the gusset plates. Regarding the design of the gusset plates for compression loads, it should be noted that unlike concentrically 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 dissipates the energy through damper component sliding. Therefore, the gusset plate should keep the braces in-plane during seismic loading. A number of methods have been introduced and explained by researchers to minimize the gusset plate out-of-plane buckling, such as using stiffeners on the gusset plate edges or using effective length factor of 2.0 for designing the gusset plates (Wu et al. 2017). Here, a compression member was considered for the gusset plate compression that is fixed-free and has a cross section equal to gusset plate thickness and pin diameter. Such a conservative assumption will ensure the elastic performance of the gusset plate against any possible out-of-plane bending with minimal displacement.

As for the connecting plates, they can be attached to the RC beam-column joint by either anchor bolts embedded within the RC member or using stud-bars which tie the connecting plates on both sides of the beams and columns. Obviously, the second method may be more suited for retrofitting plans and thus adopted here. As highlighted by literature (Maheri and Yazdani 2016), a linear varying normal component better represents the normal components forces in the connecting plate. The finite element (F.E.) modelling of the gusset plates verifies such distribution as well (Figure 3). To develop the F.E. model of the gusset plates, the obtained brace forces from the damper ultimate force (equation 12) were employed to apply the brace tensile force on the pin-hole surface of the gusset plate. It is worth noting that the ABAQUS software package (Abaqus Manual, 2014) were used to perform the F.E. analyses and check the final design. A nonlinear Elasto-Plastic material (E=200GPa) with isotropic hardening was designated to the gussets plate with yielding stress and ultimate stress of 350 MPa and 480 MPa, respectively. The finite element analyses indicated that the stress value was within the material elastic range (less than 350 MPa). The model also highlighted that the stress values around the inner bolt holes were larger than the outer bolt holes.

Another concern regarding the gusset plate design was the risk of having undesired deformation of the gusset plate which is up-scaled in Figure 3-c for better clarity. On this basis, the connecting plates in the gusset plates might get bent and deformed during the tension force and jeopardize the system performance. Based on the finite element analysis of all three gusset plates, such deformation was less than 0.5mm for all the gusset plates, thus the design seemed suitable for the test.





(a) *(b)* *(c)*

Figure 3: FE analysis of gusset plate: (a) damper brace, (b) top brace, and (c) bottom brace

3.3 RSFJ damper testing

The hysteresis behaviour of the RSFJ is a flag-shaped performance with four distinct points, which are denoted as the slipping point, the ultimate point, the unloading point, and the restored point. Two identical dampers with the same force-deformation were manufactured and connected in parallel with a telescopic circular section. The dampers were prestressed with similar numbers of disk springs to present the same slip and ultimate force of F_{slip}= 12.2kN, F_{ult}=24.4kN with displacement capacity of Δ_{ult}=46.1mm. Figure 4 represent the tuned behaviour of the two dampers.

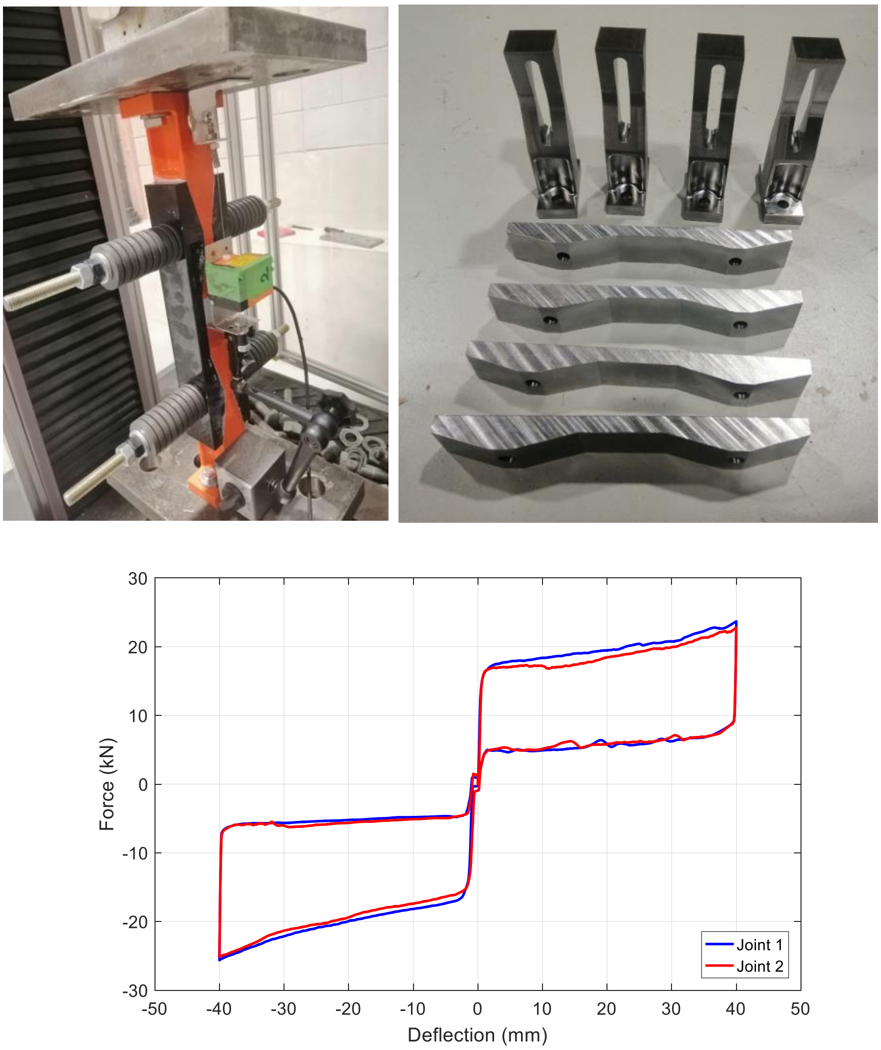


Figure 4: Experimental testing of the RSFJ toggle brace damper

4 EXPERIMENTAL TESTING OF THE RC FRAMES

In this section, the experimental testing results for the benchmark and the retrofitted frame are provided. The first frame (benchmark frame) was subjected to a progressive quasi-static cyclic pushover up to its complete failure (4.0% drift) to gain some insight about the performance of the frame without any retrofitting (the results can be seen from Veismoradi 2023). It was then noted that the bare frame would experience excessive damage for 1.5% drifts and beyond that. Then, the second frame was retrofitted with the damper-brace system and went through the similar lateral loading up to 1.5% drift.

A total gravity loading of 440 kN was applied to the frame columns (each column=220kN=0.15*P/$A_g f'_c$). The failure mode of the bare RC frame was the formation of flexural cracks at the end of columns. Based on the observed cracks patterns, it seemed reasonable to assume that the retrofitted frame would start to accumulate noticeable damage if the drift increases beyond 1.5%. Albeit, no local crush of concrete was observed on the retrofitted RC frame (It needs to be stated that due to presence of stud bars and connection plates at the corners of the retrofitted RC frame, it was difficult to witness and mark the cracks on the retrofitted frame). By comparing the cracks and damage on both bare and retrofitted frame in the same level of drift (1.5% in this case), it can be stated that the retrofitted frame showed less concrete crack and damage. This may be due to the fact that the connections could have a confinement effect on the beam-column joints and the plastic hinge area and better distribute the crack over the length of the structural member, while in the bare frame, the cracks were mostly concentrated at the beam and columns ends.

Figure 5 presents the lateral load response versus the lateral deformation of the bare frame up to 1.5% drift. The hysteresis behaviour reveals the gradual decrease of lateral stiffness during the elastic range of loading, due to cracking of the concrete, however the behaviour becomes stable in the third cycle.

The numerical pushover simulation with SAP2000 (Csi Manual, 2016) is presented as well. Fibre hinges were employed for the member nonlinearity and the materials were calibrated with the concrete cylinder tests and rebar tensile test results, to reduce the uncertainty between numerical and experimental results. The ultimate strength for the pull and push directions were recorded as 112kN and 100kN respectively, while the SAP2000 gives approximately the same results (97kN). The small difference between the numerical and the experimental results could be due to the contribution of prestressed rods and minor friction between lateral restraints and the RC frame.

As for the retrofitted test, the experimental results highlight the improved performance of the frame, in terms of energy dissipation, increased stiffness and self-centring behaviour. The pinching behaviour of the bare frame was replaced with semi-flag shape behaviour. The ultimate strength of the retrofitted system is recorded as 172kN and 162kN. Some levels of stiffness and strength degradation is witnessed in the retrofitted frame, due to concrete cracking and accumulated frame damage. Moreover, the presence of connection plates embracing the beam-column joint have helped towards distribution of concrete crack over larger area of beam and columns. Based on the performance of the toggle-bracing, the braces performed as expected without any instability issues and out-of-plane movement of the restrained node. While for this current test, the retrofitted frame showed negligible residual drifts, it is possible for the frame to present some residual displacements in higher drift demand. This indeed depends on the target level of drift for the frame, as well as the restoring force provided by the joints in the system. The numerical outcomes for a cyclic pushover with 1.0% and 1.5% drifts are compared with the experimental results in Figure 5. While the numerical results are generally in good agreement with the experimental data, some level of difference is witnessed, especially in residual displacement results, which is slightly higher in the numerical outcomes for the 1.5% drift. This is due to the difference in true nonlinear behaviour of the frame, against the simplified computer model that may not consider all the aspects of experimental RC frame testing. Such difference is not witnessed for the 1.0% drift case given the system is mainly behaving elastic in this drift ratio.

The damper displacement during the cyclic loading is summarized in Table 1. Based on the test results, the amplification factor in the pull and push directions of the system is evaluated as 1.16 and 0.98, respectively. The amplification factor is a parameter that can be altered based on the damper and brace length arrangement. The damper displacement from numerical results also provides very close results. The results shown in the table also highlights the capability of the proposed system to be activated within a small drift of the RC frame. As an illustration, for the 0.25% drift of the RC frame (5mm frame lateral deformation), the damper has already mobilized more than 2mm.

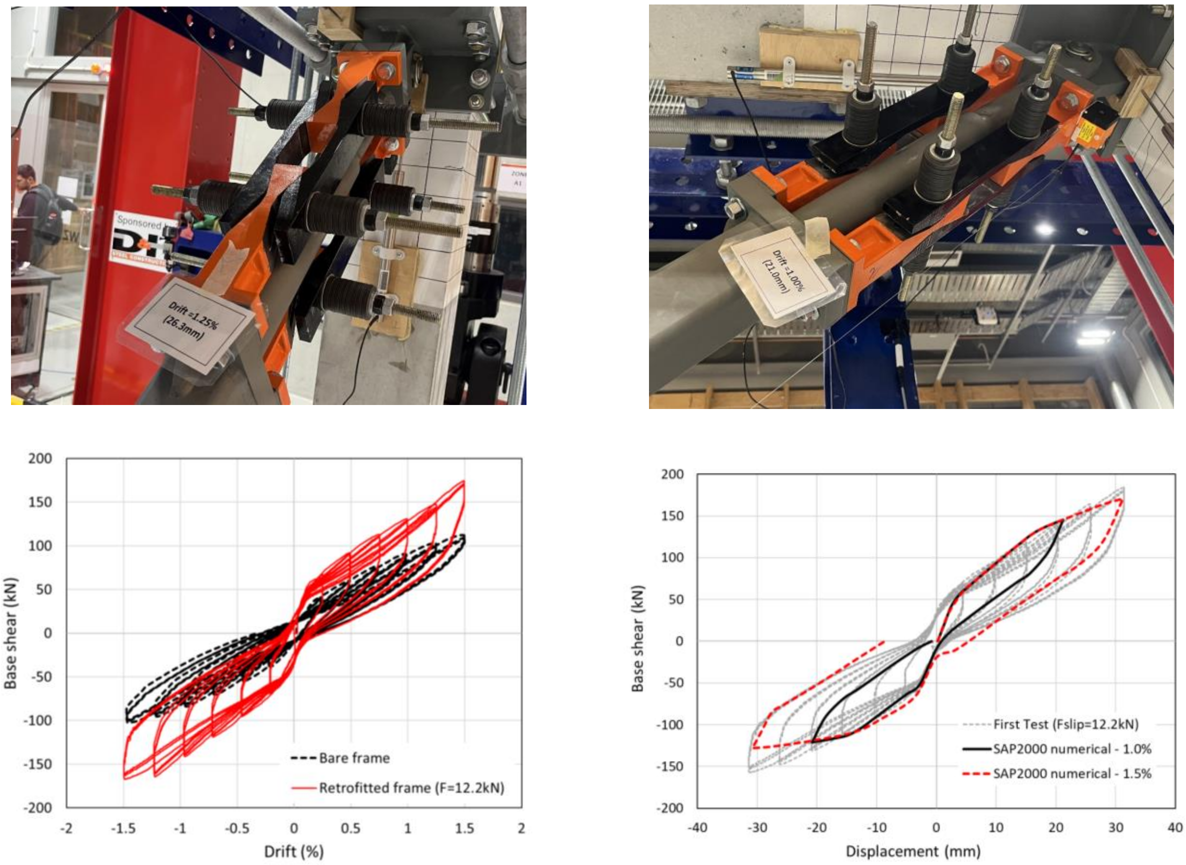


Figure 5: Experimental testing of the retrofitted RC frame and comparison to the bare RC frame

Table 1: Recorded damper displacement during cyclic testing

Parameters	Unit	Frame Drift (%)					
		0.25	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**
Frame displacement	mm	±5.3	±10.5	±15.8	±21.0	±26.2	±31.5
damper displacement (pull)	mm	+3.2	+9.3	+16.3	+22.1	+29.1	+36.6
damper displacement (push)	mm	-2.4	-7.5	-13.0	-18.3	-23.6	-30.7

5 SUMMARY AND CONCLUSION

This paper investigated the efficiency of the RSFJ-toggle bracing system. Two small-scale identical RC frames were constructed and subjected to a quasi-static cyclic loading and the results of the benchmark frame and the retrofitted frame were compared. The following conclusions and recommendations are drawn:

1) The overall performance of the retrofitted frame improved in terms of stiffness, strength and energy dissipation features. The ultimate strength almost doubled and energy dissipation increased 285%. It needs to be pointed that such results are only applicable to the current experimental test and may not be generalized to other RSFJ-toggle bracing systems.
2) The proposed retrofitting system is capable of being activated in small drift values (0.25%) and preserves the RC frame.
3) The retrofitted braces performed as predicted without any instability issues and out-of-plane buckling.
4) The connection plates were able to preserve the RC frame from concentrated damage at the beam and column ends and provide some level of confinement for the beam-column joints. This was witnessed by lesser number of cracks on the retrofitted RC frame up to the 1.5% drift.

5) It needs to be stated that such retrofit may impose higher base shear on the foundation of the system. This needs to be considered by engineers for a proper retrofit design.
6) The results and findings from this paper could be used for the design of the toggle-brace retrofitting of RC frames with other types of dampers such as traditional friction dampers. Obviously, such dampers may provide higher added damping to the retrofitted system. However, they might be more susceptible to residual drifts.

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