Application of Low Damage Tension Braces in Top Extensions of Existing Buildings: A Case Study for Seismic Upgrade

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ABSTRACT

Tension-only braces are generally used as diagonal cross members (rods, flat bars or similar) to resist lateral loads. The application of these braces has been limited to low-rise buildings (generally up to two stories) by most standards and is not recommended for seismic applications. This is firstly because of the lack of damping and ductility and, secondly, the absence of a reliable over-strength mechanism. When these braces are combined with resilient self-centring devices, the product is a low-damage system with considerable hysteretic damping that eliminates the issues mentioned for traditional tension bracing systems. This paper describes a unique case study where innovative tension-only braces are used for seismic upgrading and refurbishment of an existing concrete building. The 48 Greys Ave is a 10-storey office building in central Auckland undergoing a major upgrade that includes adding a new upper level to the structure. Although the seismic risk at this site is relatively low, the addition of the new floor meant that it could experience high accelerations in a design-level earthquake. The paper describes the project and elaborates on the innovative approach adopted and the analysis method. It also includes information on the resilient devices and physical tests of them before they are installed. This paper's findings will interest engineers and researchers passionate about low-damage design and innovative seismic upgrade solutions.

1 INTRODUCTION

Following the Canterbury earthquake sequence (2010 to 2012), it was observed that most of the structures with steel lateral load resisting systems have performed very well, considering the severity of the seismic events, most particularly structures with seismic resisting systems such as Eccentrically Braced Frames (EBFs) or Concentrically Braced Frames (CBFs) (Bruneau and MacRae 2017). However, the structures were designed for the 'life-safety' criteria so post-disaster repair costs (if the structure is repairable) and the associated business downtime have significantly affected the economy of the recovering city. Moreover, previous studies have demonstrated that residual drifts of more than 0.3% can impact the structural functionality and more than 0.5% require realignment which is difficult and would probably result in building replacement. Even residual drifts of 0.15% will require realignment of lift shaft guide rails, involving significant cost and disruption (Clifton et al. 2011).

With the growing acknowledgement of the post-event economic impacts on society has come the increased demand for damage avoidance systems that can deliver a high resistance level against severe earthquakes, allowing buildings to be rapidly returned to service, with negligible or no residual displacement and either requiring no maintenance or maintenance which can be delayed and undertaken at a time to suit the client.

The Resilient Slip Friction Joint (RSFJ) technology (2015) is a recently developed damage avoidance technology that has already been implemented in several projects. This technology provides self-centring behaviour and seismic energy dissipation in one package. It also includes a built-in collapse prevention secondary fuse function that adds more resilience to the system in case of a seismic event larger than the design level. Hashemi et al. (2017) experimentally verified the flag-shaped hysteresis and the self-centring characteristic of the RSFJ.

Figure 1 shows the components and the assembly of the RSFJ. In this joint, the energy is dissipated by frictional sliding of the moving plates while the specific shape of the ridges combined with the use of disc springs provide the necessary self-centring behaviour. At the time of unloading, the restoring force induced by the elastically compacted disc springs is greater than the resisting frictional force between the sliding parts. Thus, the elastic force of the discs re-centres the middle plates to their original stationary position. Figure 1(c) shows the device at rest when the disc springs are partially compacted. When the force applied to the joint overcomes the resistance between the clamped plates, the middle plates start to move and the cap plates start to expand until the joint is at the maximum deflection and the discs are flat (see Figure 1(d)). Figure 1(b) displays the load-deformation behaviour for the RSFJ.

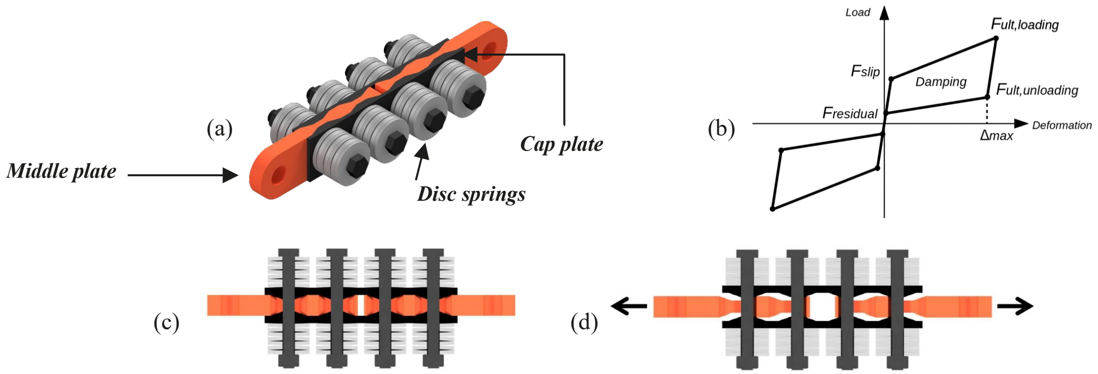

Figure 1: Resilient Slip Friction Joint (RSFJ): (a) assembly, (b) hysteresis, (c) the joint at rest, (d) the joint at the maximum deflection

2 THE RSFJ TENSION-ONLY BRACE

Figure 2 schematically shows the RSFJ tension-only concept. In this concept, the RSFJ device is in series with the diagonal tension members forming an x-braced system effective in tension only so there will be no global buckling in the system. Rebars, threaded rods, or any other type of tension-only element can be considered for the diagonal members resulting in an economical damage avoidance lateral load-resisting system. Full-scale experimental tests by Bagheri et al. (2019). have indicated that the hysteretic performance of this system is similar to a system with tension/compression braces that have equal strength and stiffness in both directions of loading in the plane of the frame. Figure 3 shows the test results that were done dynamically based on the AISC (AISC 2010) standard up to a lateral drift of 5%

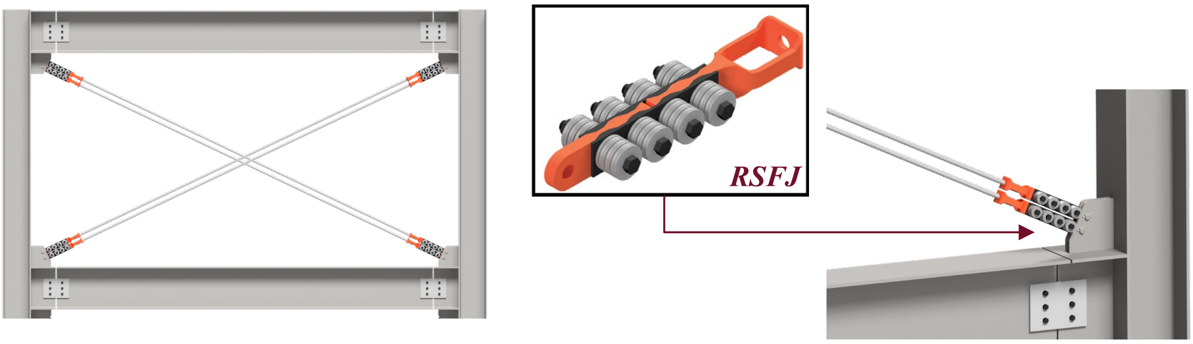

Figure 2: The RSFJ tension-only brace concept

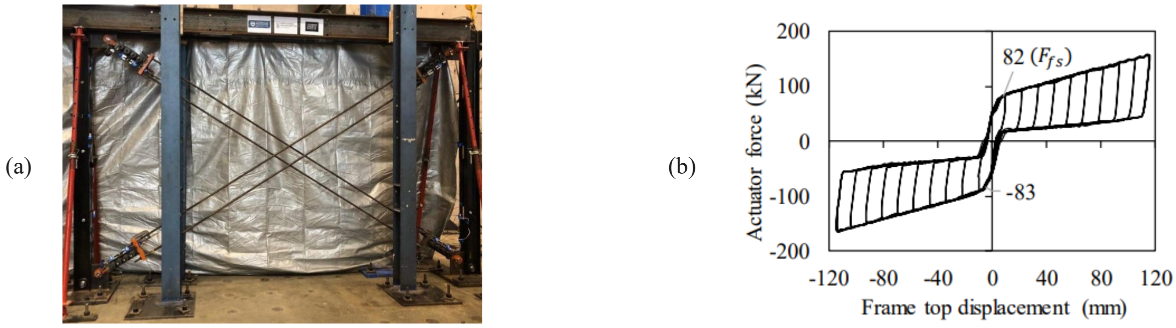

Figure 3: Experimental verification of the RSFJ tension-only brace: (a) test setup (b) test results

3 INTRODUCING THE PROJECT

The case study building is located at the intersection between Greys Avenue and Mayoral Drive in the Auckland City Centre. The building consists of a ten-story reinforced concrete structure with a maximum height of approximately 37 m above the basement ground level. TEKTON Consulting Engineers Limited has been selected by the client to carry out the design and provide options to add new stories to his existing 10-story building. The final commercial decision and TEKTON's brief were to top the existing building with a high-end commercial floor. Figure 4 shows the Architectural elevation of the existing building and the proposed extension.

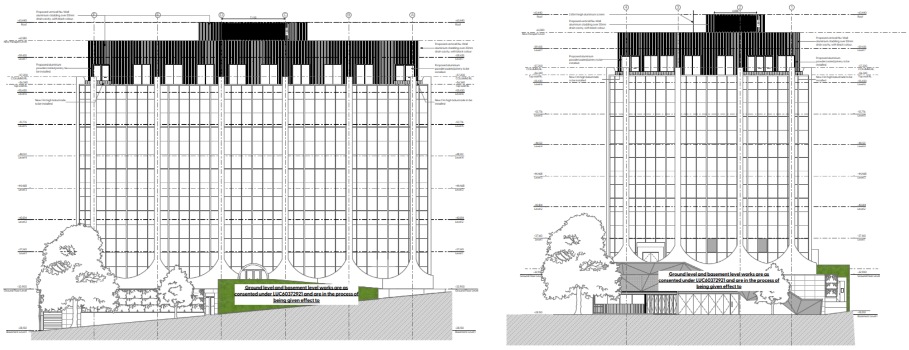

Figure 4: Architectural elevation of the existing building and the proposed extension

4 DESIGN APPROACH AND CHALLENGES

The engineering challenge for this building was to find a solution that wouldn't compromise the integrity of the existing building while adding the additional floor, ensuring a cost-efficient approach without the need for structural improvements to the supporting structure. At the same time, the cost of the new structure needed to be minimized, and it should be immediately occupied after a significant earthquake. Due to the considerable distance from the ground, high accelerations were expected at the top of the existing building, potentially imposing significant forces on the supporting structure and leading to remedial work. As can be seen in Figure 5, the ground accelerations are transmitted to the top floor which can play a key role in the seismic response of the proposed extension and the overall building. Figure 6 shows the calculated accelerations at the top of the existing building by taking the conservative value of S_p=1.0 μ=1.0 on the existing building.

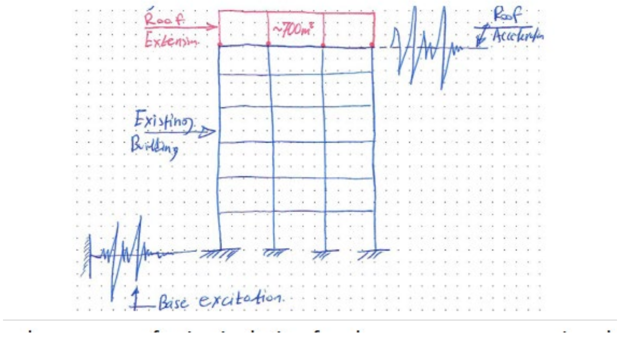

Figure 5: Schematic representation of the ground accelerations transmitted to the top floor

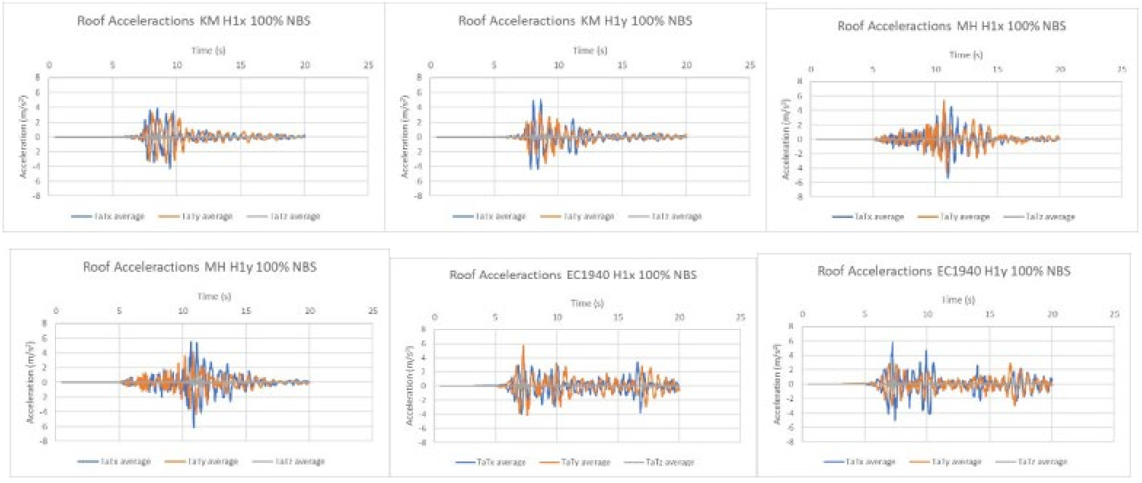

Figure 6: Existing building roof accelerations used for the design of the new extension

The idea of using the existing concrete lift core to support the new floor laterally was quickly dismissed because the concrete core over the existing roof was not initially designed to support additional seismic masses, necessitating significant remedial work. Following a comprehensive options analysis, it was chosen to isolate the new structure from the existing concrete lift core, leaving an appropriate separation gap and providing a new lateral resisting system to the perimeter of the new extension. This system could absorb energy during earthquakes, reduce seismic forces on the supporting structure, and eliminate the need for remedial action. Given that the columns of the new extension didn't align with the columns below, new drag beams were introduced at the top of the existing building to transfer the new column reaction forces to the existing columns (see Figure 7). Figure 8 shows the typical braced bay at the perimeter of the proposed extension. The separation gap was sized from the Time History Analysis of the existing structure considering the max lateral displacements of the new structure at the MCE earthquake. Allowance was made for the existing lift overun been deformed out of phase with the new structure

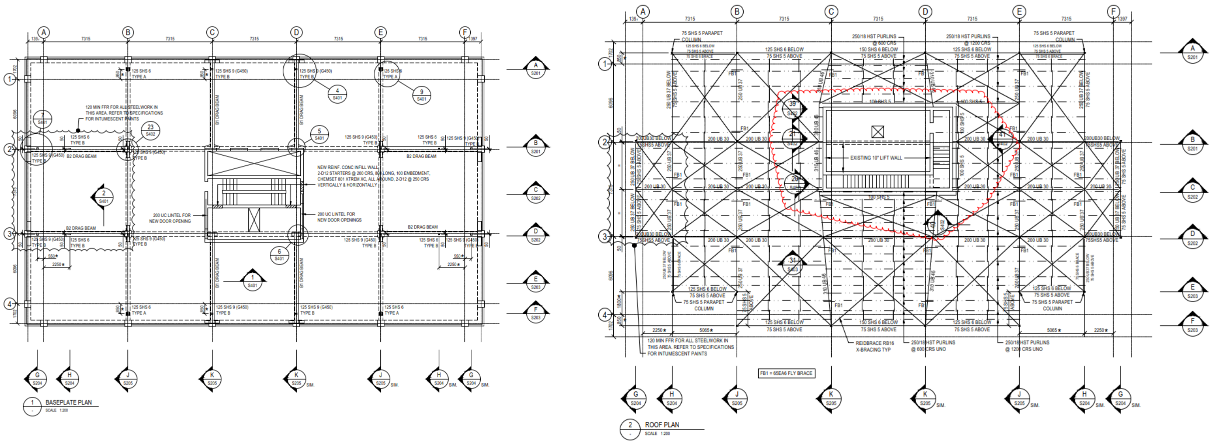

Figure 7: Exiting top floor (left) showing the new drag beams and new roof layout (right)

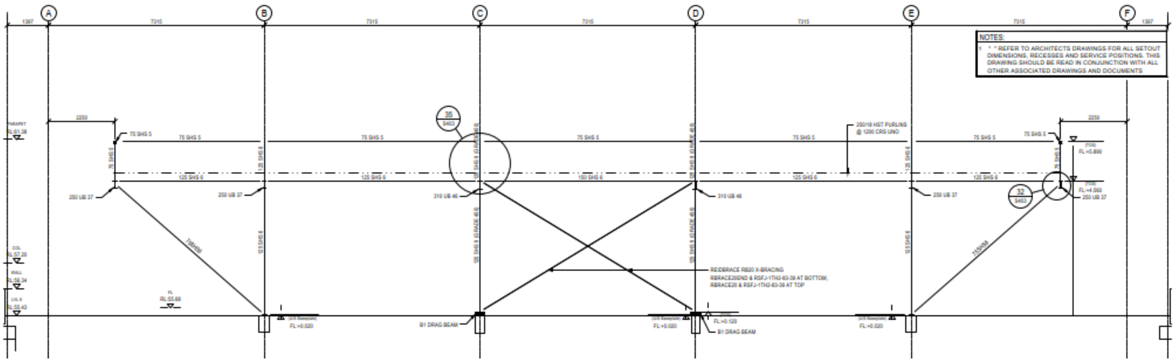

Figure 8: Typical braced bay at the perimeter of the new building

Before modelling the extension, A detailed modelling and non-linear time history analysis of the existing building was carried out using DIANA Finite Element Analysis software. This assessment includes the non-linear behaviour of the reinforced concrete members under various earthquake scenarios (ground motions), with varying intensities, that provides a realistic representation of the building behaviour in an earthquake event. The purpose of the model was to evaluate the realistic time histories at the top floor of the existing building, where the new extension will be founded. The time history analysis would have taken into account any dynamic amplifications due to potential resonance effects.

The next step of the design process was deciding on the new lateral system. It was decided by the design engineers that a low-damage solution is considered that focuses on building earthquake-resilient structures that preserve life and maintain the primary structure for easy repair. Accordingly, the RSFJ technology has been selected for this purpose. To optimize the new structure's design and reduce earthquake forces through ductile behaviour, it was proposed to use tension Reid braces with RSFJ joints at both ends. Advanced non-linear analyses provided the most realistic seismic performance, including the RSFJ joints at the end of the tension braces. Coordination with the client and the cladding/window supplier was necessary to ensure the low-damage design objectives were satisfied. A typical detailing for this type of brace is shown in Figure 9(a).

A numerical model has been created in commercial software for the extension building that utilised tension-only RSFJs and iterations were made to optimise the performance. Two RSFJs per brace were tuned to accommodate higher drift demands based on a maximum roof acceleration. Firstly, pushover analyses were performed to evaluate ductility levels and then roof accelerations from the existing building have been used as input to perform nonlinear dynamic time-history simulations. From pushover analyses, ductility factors around μ=3 have been achieved in both main directions. This was later verified by the time-history analyses. The inherent damping of the structure with steel tension-only braces was kept at 2%. The maximum response drift was 1.2% and 1.55% in X and Y directions, respectively. These drifts were calculated by averaging displacements calculated at nodes close to the centre of mass. Figure 9(b) shows the general arrangement of the model developed and Figure 10 shows the hysteretic response of the structure and the braces under one of the load cases. Overall, a high ductility value has been achieved while keeping the structure elastic for SLS1 actions and restricting the inelasticity in the tension braces for ULS actions. An over-strength factor of 1.35 has been used to design the brace connections and the surrounding members. The dynamic analyses performed demonstrated a fully self-centring behaviour owing to the flag-shaped load-deformation response of the RSFJ braces and the fact that the rest of the structure remained elastic.

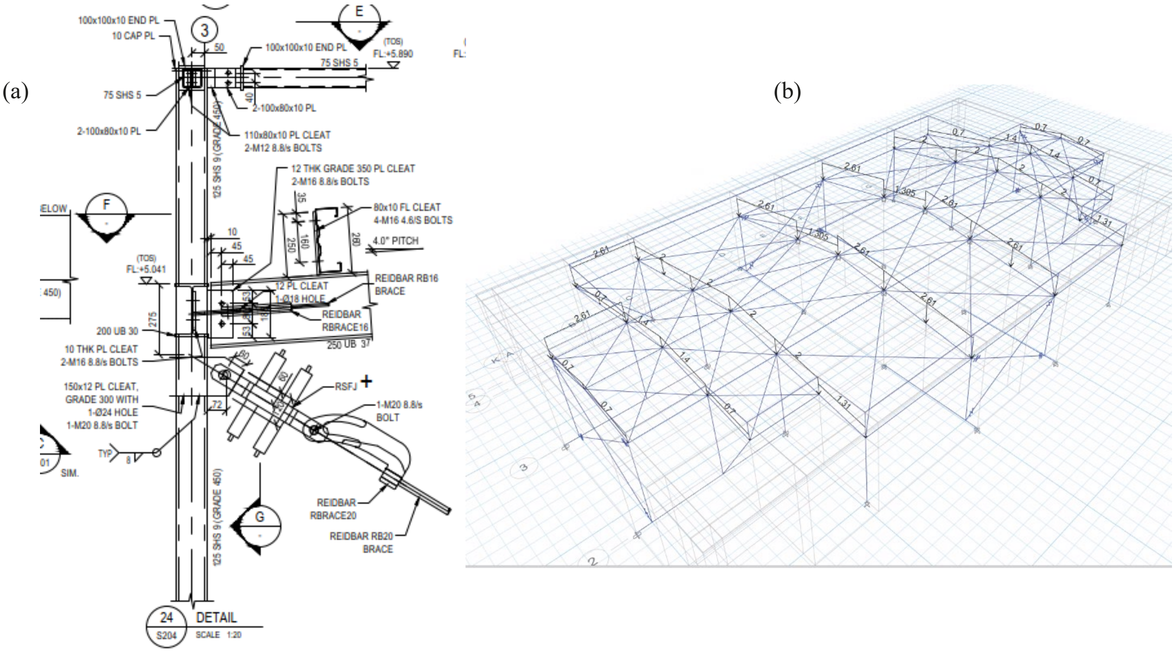

Figure 9: (a) typical detail at the end of the tension brace featuring RSFJ joints combined with the proprietary Reidbrace (b) numerical model developed in commercial software

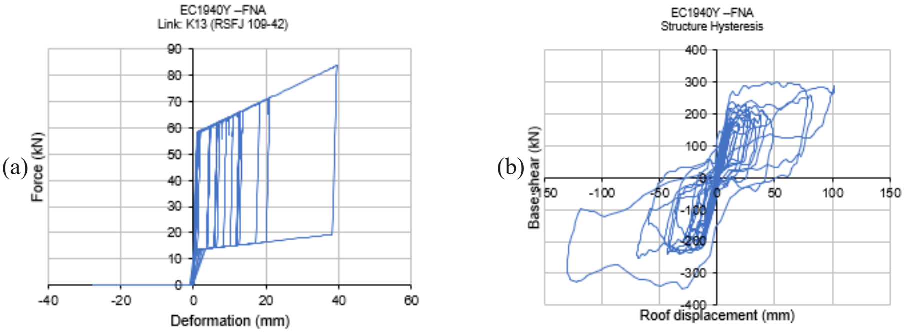

Figure 10: Results of dynamic analysis for one of the load cases: (a) overall performance (b) link hysteresis

5 FABRICATION AND PRODUCTION TESTING OF SEISMIC DEVICES

From the analyses described in the last section, the specification indicated in Figure 11(a) was specified for the devices. The RSFJ were manufactured to achieve the target performance in terms of load capacity (F_{ult}), displacement capacity and hysteretic damping. Then, they were subjected to repeated cyclic loading to demonstrate the stability of performance. Figure 11(a) shows the universal testing machine used for the production testing. Figure 11(b) depicts the load-deformation behaviour of one of the devices during production testing (red dashed lines show the specified performance) and Figure 11(c) shows the on-site arrangements. As can be seen, the devices were mounted on tension Reid braces before installation.

6 CONSTRUCTION

The initial construction phase involved positioning the drag beam to redistribute structural weight onto the existing concrete column. The installation of specified epoxy anchor fixings at the drag beam locations posed several challenges. Accordingly, the anchor fixings have been assessed and three solutions are proposed: (i) Loosening the nuts on the installed anchors and relocating the beams, followed by scanning and drilling through the existing concrete where feasible (ii) Drilling new holes adjacent to existing ones until they avoid hitting reinforcement and filling abandoned holes (iii) Revising the anchor fixings based on the provided markup detail drawing showing the actual length of all anchors at the drag beam locations. Ultimately, the third option was deemed more practical and cost-effective compared to the other alternatives.

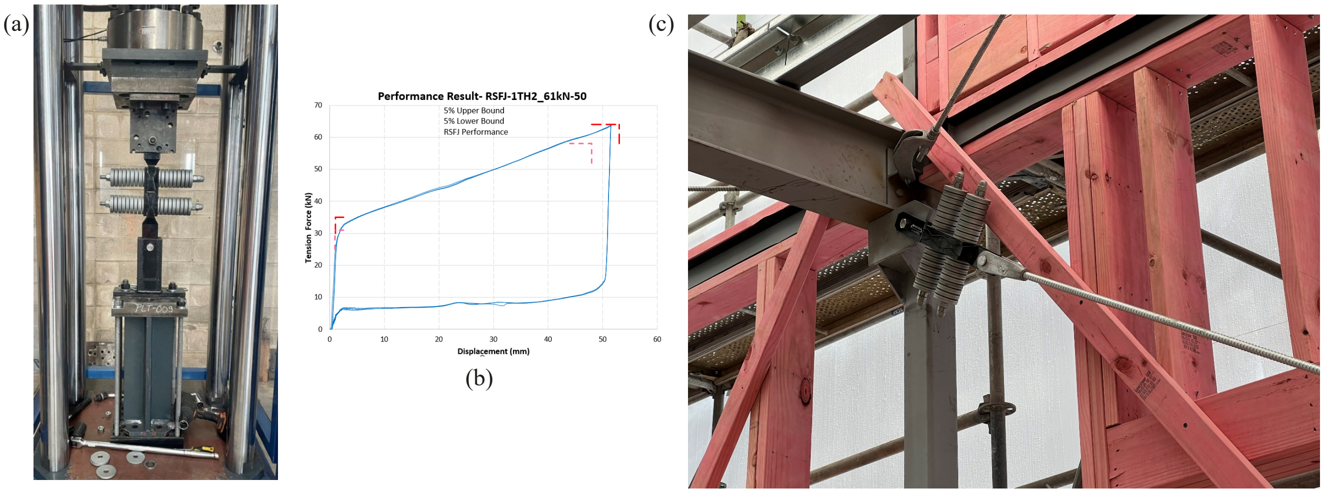

Figure 11: Production testing and installation of the RSFJs: (a) test setup arrangement (b) load-deformation behaviour (c) installation on site

Another challenge arose during the placement of the RSFJ connection due to its clashes with the wall proposed by the architect. To rectify this, it was decided to offset the brace to prevent any clash with the wall, leading to the design of a new connection to resolve this issue. Figure 12 shows the details. The affects of these modifications were verified before the implementation of the final construction detailing.

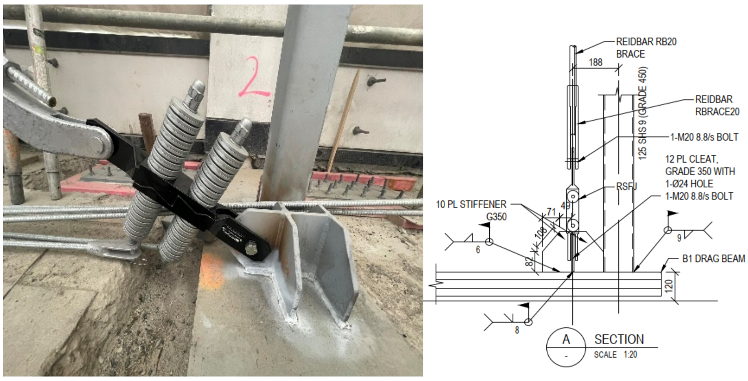

Figure 12: Connections of the tension-only RSFJ to the structure

7 CONCLUSIONS

This paper presents a brief introduction to the innovative RSFJ tension-only bracing system and describes a case study where this technology has been used to add a new storey to an existing 10-story structure in Auckland CBD. In general, the following concluding points can be drawn:

- The proposed structure does not alter the performance of the existing building or add any loads to it, thereby maintaining the capacity of the existing building.
- The collaboration between TEKTON, Tectonus, Ramset-Reid, and the proposed system resulted in a successful project that satisfied everyone.
- The RSFJ joints could be utilized for low-damage design alternatives to tension brace-only systems for buildings where reduction of forces is required through the ductile behaviour of the building and performance objectives are required to be met in the earthquake design. A fully self-centring behaviour has also been achieved.
- The use of low-damage technologies is still a project underway and will most likely change the way we do Engineering in the future.
- Specific requirements and design performance criteria for structural and non-structural elements are yet to be defined in the National Standards, and therefore, the design of these systems is considered an alternative design to the New Zealand Building Code.

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