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ADVANCEMENT OF A NOVEL SELF-CENTRING CONCENTRICALLY BRACED FRAME (SC-CBF) STRUCTURAL STEEL SYSTEM FOR SEISMICALLY ACTIVE ZONES

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***Abstract**: The self-centring concentrically braced frame (SC-CBF) is an advanced structural system that has been specifically designed for regions prone to earthquakes. It offers several advantages over traditional concentrically braced frames (CBFs), including the capability to replace energy-dissipative structural elements effortlessly after a significant earthquake. This is achieved by using the strategic placement of post-tensioning elements along the beams to create a rocking joint behaviour, which helps absorb seismic energy and reduce the overall seismic demand on the structure. This feature enables the structure to return to its original position. Therefore, residual deformations that compromise the integrity of traditional CBFs can be eliminated. In the past 10 years, a novel SC-CBF system was proposed and developed by University of Galway for use in CBF buildings subjected to natural hazards such as earthquakes. A series of laboratory experiments including cyclic pushover tests and shake table tests were conducted to investigate the behaviour of the novel self-centring system. The finite element numerical model used to analyse the self-centring braced frame system has been developed and validated using OpenSees. Both experimental and numerical analyses demonstrated that the SC-CBF behaves as expected under various loading protocols. The structure returns to its initial vertical position after large earthquakes while dissipating energy through concentrically bracing members and, hence, keeping non-dissipative structural elements safe. Furthermore, guidelines and design procedures for the SC-CBF system are being developed. This series of research works help ensure that the SC-CBF system can be effectively adopted by industry, leading to overall improved seismic performance and greater resilience in CBF steel structures.*

1. Introduction

Over the past three decades, extensive research has been conducted into different lateral seismic resisting structural systems. Ensuring that lives are safe is an underlining principle of all design codes and research. However, typically requirements are more onerous than that, and minimising damage to a building and its contents is an important design consideration, as is ensuring that buildings can be relatively easily repaired after an earthquake if damage does occur. Many research papers are devoted to investigating ways to eliminate or minimise residual deformations of inter-story drift after earthquake actions and the associated structural ductility requirement.

Among the conventional lateral force resisting structural systems are special moment resisting frames (SMRF), buckling restrained braced frames (BRB) and concentrically braced frames (CBF), which control structural damage through ductile framing systems that rely on the ductile property of structural components. During moderate to severe earthquakes, these conventional lateral resisting systems undergo inelastic deformations (residual deformations) in non-structural and structural elements (Goggins et al. 2006). Examples of this behaviour were observed during the 1994 Northridge Earthquake, 1995 Kobe Earthquake, 1999 Chi-Chi Earthquake, and 2011 Christchurch Earthquake. Structural and non-structural damage lead to economic losses resulting from repairing, rebuilding and downtime. However, residual deformations in structures due to severe earthquake hazards can make repairing and/or replacing both damaged structural and non-structural elements difficult, increasing downtime and repair costs (O'Reilly et al. 2012a; O'Reilly et al. 2012b; O'Reilly 2013). Therefore, there is a need to eliminate residual drifts that can lead to unstable and/or unusable structures. As conventional systems have limited "elastic" drift capacities, many research studies have attempted to develop alternative solutions (Xiong et al. 2017).

Self-centring structural systems that eliminate or minimise residual drift of the structural system can be utilised in seismically active regions, where the system allows dissipative structural elements to be easily replaced after a large earthquake. Not only does this improve the resilience and robustness of the structure, it also improves its sustainability. Self-centring systems make strategic use of post-tensioned interfaces between the main structural elements (such as beam-column) to create rocking joint behaviour under seismic loads. A key feature is that the structure will return to its original position after an earthquake, eliminating residual deformations that are typically observed for traditional steel structures after large earthquakes.

In this research, an overview of the development of a novel self-centring steel concentrically braced frame (SC-CBF) system is presented. The system was initially designed by O'Reilly and his colleagues (O'Reilly et al. 2012a; O'Reilly 2013; O'Reilly and Goggins 2021; O'Reilly et al. 2012b) in 2012. A series of static and shake table tests were carried out to verify the concept of this self-centring frame system. In the research work of O'Reilly and Goggins (2021), cyclic pushover tests were prepared and performed in the large structures laboratory of University of Galway. A SC-CBF system with replaceable bracing members was installed and tested under displacement-controlled cyclic loading. This SC-CBF was integrated into a three-dimensional (3D) structure and was tested on the shake table in the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in North Macedonia (Goggins et al. 2020; Goggins et al. 2021). During the shake table testing, two specific ground motion scenarios were selected and applied as controlled table acceleration histories at various scale factors. In addition to the full-scale experimental studies, computational analyses were performed using the OpenSees framework. This paper gives a brief overview of the experimental and numerical testing programme conducted cover the last 10+ years to develop and validate this novel SC-CBF system for use in moderate to severe seismic hazard regions.

2. Methodology

2.1. Concept of SC-CBF

The development of this novel SC-CBF system at the University of Galway commenced in the research work of O'Reilly et al. (2012a). This novel system for CBFs utilised a horizontal post-tensioning approach for the self-centring system. Figure 1 depicts the arrangement of the SC-CBF and the connection behaviour, as detailed by O'Reilly and Goggins (2013a) and O'Reilly and Goggins (2013b). As can be seen from Figure 1, the beams and columns of the SC-CBF system are pin connected with post-tensioning (PT) strands utilised to hold the whole frame and prevent the rotation of the beam-column connections. It should be noted that the strands are not required to resist shear forces, as these are transferred through shear connections between the beams and columns, as can be seen in Figure 2. With the lateral displacement imposed, the deformation of the frame can be divided into two stages. In the first stage, there is no relative movement between the beams and columns, which benefit from the PT forces keeping the gap closed between the beams and columns. In other words, the whole structure behaves like a dual system of a moment resisting frame (MRF) and concentrically braced frame (CBF). However, with the increase of the lateral displacement, the moment at the beam-column rocking connection increases and a gap starts to develop between the beam and column

(Figure 1 (a)). Under a moderate to large earthquake excitation, the beam starts to rock against the column. Under this rocking mechanism, the concentrically braced members can dissipate energy through plastic deformation and, hence, the beams and columns are protected. The lateral force versus displacement response of the SC-CBF can be treated as the combination of the bracing members and the PT system. As shown in Figure 1 (b), the SC-CBF is expected to have a flag-shaped hysteretic loop under cyclic lateral loading. More information about the concept of SC-CBF can be found in O'Reilly and Goggins (2021). A design methodology for the SC-CBF system using force-based design in accordance with provisions in Eurocode 8 is presented in Alwahsh et al (2024a).

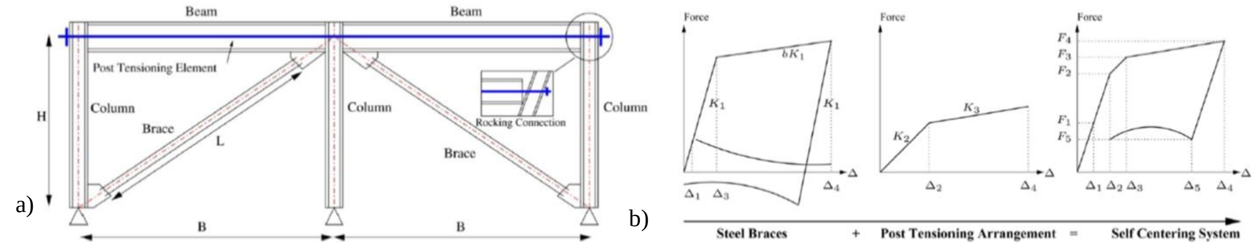

Figure 1: (a) Schematic arrangement of a SC-CBF, (b) hysteresis behaviour for the SC-CBF (adapted from O'Reilly and Goggins 2013a).

2.2. Pushover Tests

Experimental quasi-static pushover analyses were conducted at the large structures laboratory, University of Galway, to evaluate the design concept of the self-centring system. In the experiments, the self-centring frame (Figure 2) had been tested under quasi-static cyclic loading following the ECCS (1986) load protocol. Structural Hollow Section (SHS) tubes with four different geometries were selected as the energy dissipating members. The tests were conducted until the braces failed mechanically (plastic deformation, buckling, or rupture). During testing, the rocking mechanism of the beam-column connections and the plastic deformation of the bracing members were monitored through displacement transducers and strain gauges. Further details regarding the pushover tests can be found in the research work of O'Reilly et al. (2012a), O'Reilly et al. (2012b), O'Reilly (2013) and O'Reilly and Goggins (2021).

Figure 2: The SC-CBF tested in the large structures laboratory, University of Galway (adapted from O'Reilly and Goggins 2021).

2.3. Shaking Table Tests

The shaking table test campaign took place within the framework of the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA), using a full scale model of a SC-CBF system, including the structural steel frame, steel bracing members, pre-stressed steel strands, and an additional mass system. The objective of the test was to examine the seismic performance of the novel self-centring steel concentrically braced frame described above during dynamic response to earthquake loading. Figure 3 shows the structure installed on the seismic shaking table at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) located in Skopje, North Macedonia. Steel ingots, weighing 20 tonnes, were placed on the roof. The middle frame shown in Figure 3(a) was the SC-CBF which provides the lateral force resistance and self-centring behaviour. The two external frames were gravity frames, which only provided vertical support to the roof mass.

In the shake table test, four different bracing configurations were examined, incorporating different steel structural hollow section (SHS) braces and gusset plates. The structure was subjected to ground motions, which were selected from real earthquake events, with different scale factors. The structural response was evaluated using data from strain gauges, load cells, displacement transducers and accelerometers. The measured results provided information on the important parameters, such as the tensile and compressive strength of the braces, post-buckling capacity, gusset plate strains, post-tensioning force, maximum drift and residual displacement. Further insights into the shaking table tests are given in Goggins et al. (2020), McCready et al. (2020), and Goggins et al. (2021).

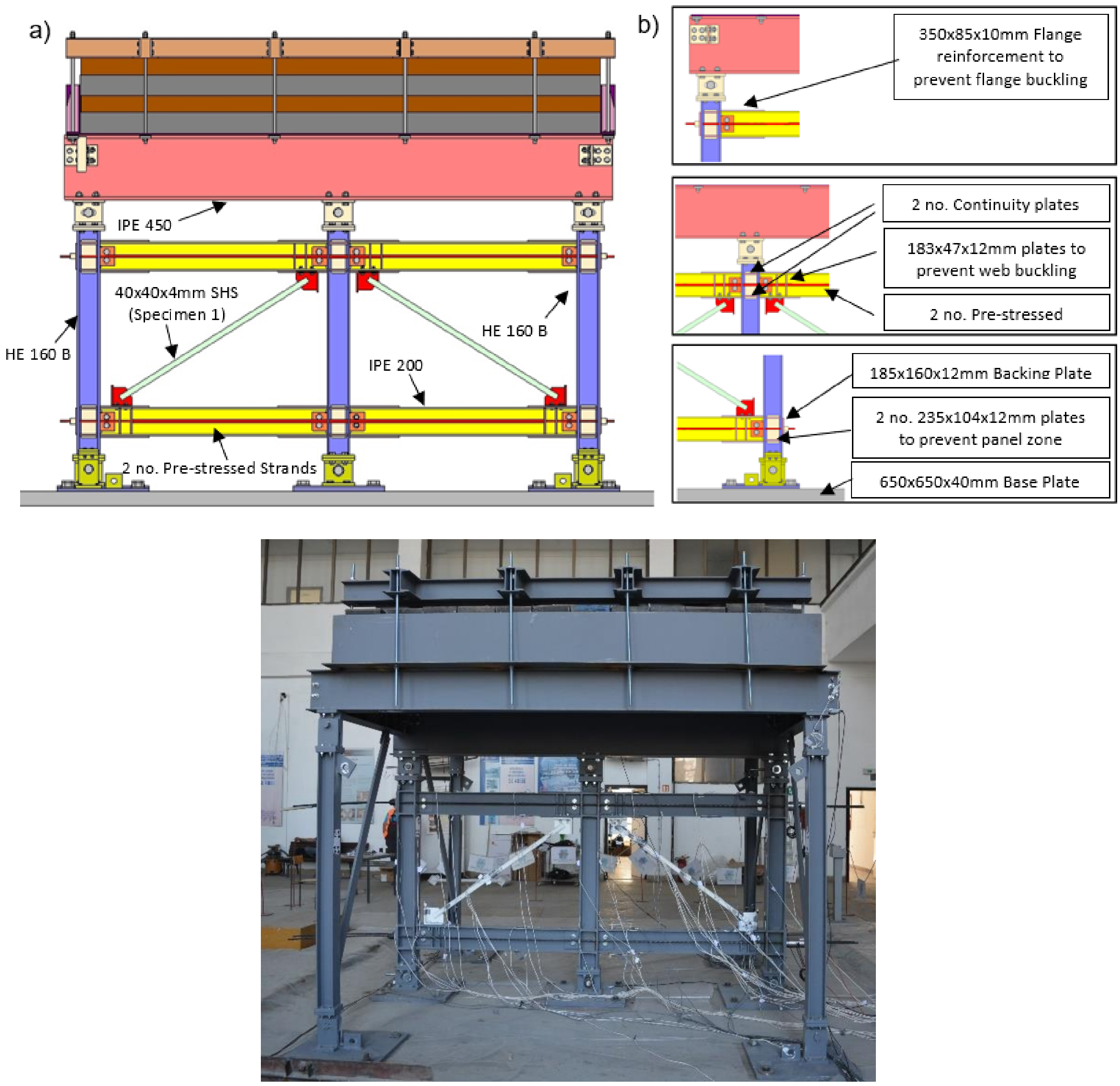

Figure 3: Overview of the IZIIS shake table test set-up of the SC-CBF system (Goggins et al., 2021)

2.4. Numerical Modelling

A finite element model was developed to predict the structural behaviour of the SC-CBF (Alwahsh et al, 2024b). The models were generated and analysed within the OpenSees framework. Figure 4 shows the schematic analogy and modelling assumptions of the main lateral resisting system of the self-centring CBF frame.

In this research, only the central SC-CBF frame that was tested on the shake table in IZIIS is modelled, as the two gravity frames do not contribute to lateral resistance. The model incorporates multipoint constraint elements to replicate the rocking mechanism in the beam-column connection and nonlinear fibre elements to simulate the plastic deformation of braces during energy dissipation. The dimensions of the main structural elements (beams, columns, and braces) in the numerical model match those used in the experimental shaking table setup. The beams and columns, which remain elastic under loading, are represented using 2D beam-column elements. For the brace members, four nonlinear displacement-based elements are employed along the member length, each with five integration points per element. A 0.5% initial imperfection is introduced to induce global lateral buckling of the braces. The brace cross-section is discretised into 20 fibres along both the width and depth and five fibres along the thickness. The connection of the braces to the beam flanges is modelled as rotational springs to capture the gusset plate deformation, following the approach outlined by Hsiao et al. (2012). Post-Tensioning (PT) elements are modelled using truss elements with an elastic material model, and contact elements are used at the beam flanges for the rocking connection. Further information about this model can be found in Alwahsh et al (2024b).

3. Results and Findings

3.1. Pushover Test Results

In all pushover tests, gaps between the beams and columns were observed with the increase in lateral displacement, indicating the development of the expected rocking behaviour. Significant plastic deformation of the concentrically braced members was developed under the cyclic lateral displacements, as seen in Figure 5 (a). However, no damage was observed in the beams, columns or PT strands. This demonstrates that most of the imposed energy was dissipated through bracing member deformations, proving the design concept of the SC-CBF structure. Since only the braces suffered plastic deformations, repair time and costs after the moderate to large earthquake loading are reduced significantly. The lateral load versus drift ratio plot from a representative test (with SHS 40x40x4.0 braces installed) is shown in Figure 5 (b), where the drift ratio represents the inter-storey displacement to storey height. It can be seen from this figure that a flag-shaped

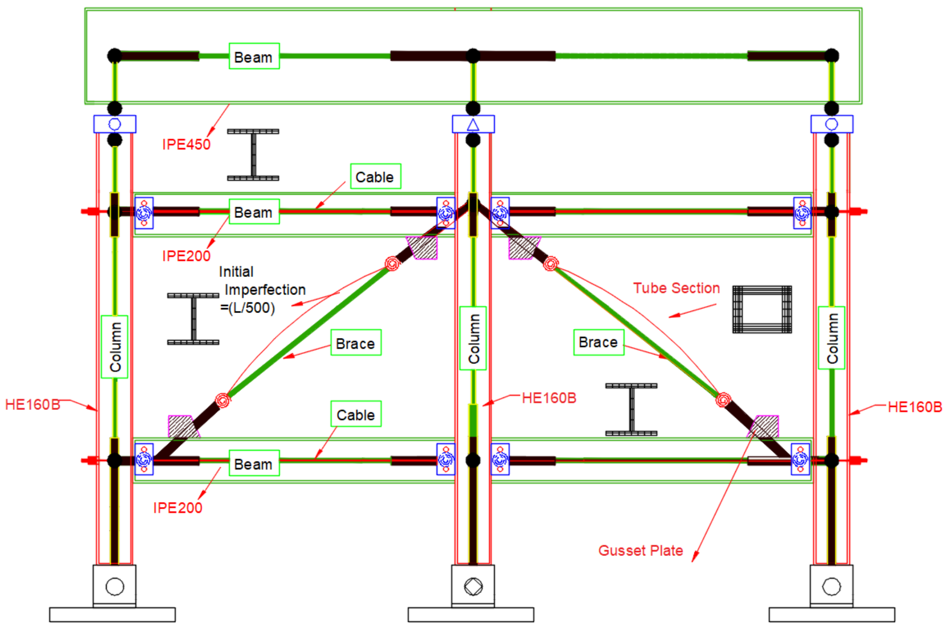

Figure 4: The numerical model concept of the SC-CBF system investigated in the shaking table tests.

hysteretic curve was achieved, indicating that the SC-CBF behaved in the intended manner. More detailed test results can be found in the research work of O'Reilly and Goggins (2021).

In light of the conclusions drawn from the overall response of the test frame to lateral loading, these pushover tests provide strong validation for the behaviour of the novel SC-CBF. These findings set the stage for subsequent experimental and numerical investigations, indicating the potential for this novel self-centring CBF as a promising design system for addressing major seismic loading challenges in future structural engineering projects.

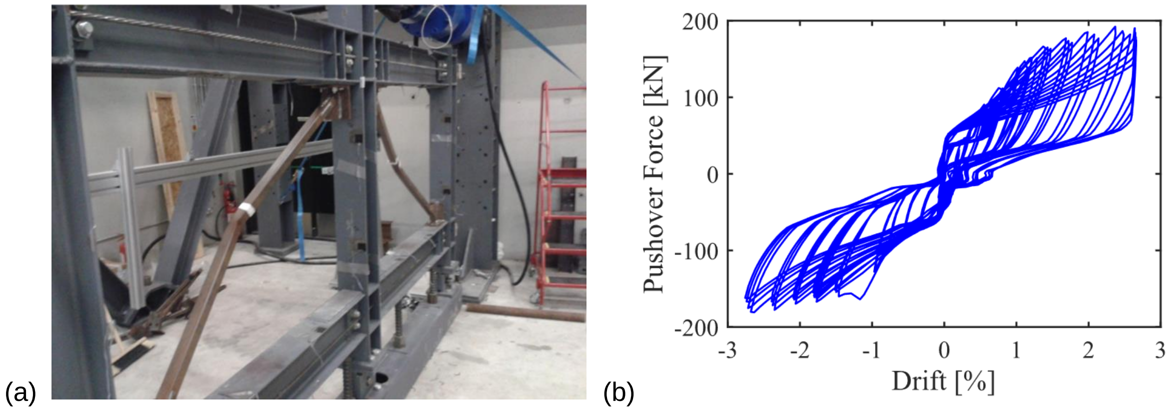

Figure 5: (a) Plastic deformation of the brace SHS 40x40x4.0, (b) force versus drift ratio plots of the SC-CBF with SHS 40x40x4.0 braces installed (O'Reilly and Goggins 2021)

3.2. Shaking Table Tests Results

A comprehensive shake table testing program was completed, which included four different brace sizes, two distinct ground motion scenarios, and a range of earthquake scale factors. The shake table tests allowed the investigation of the seismic performance of the SC-CBF under realistic earthquakes, particularly focusing on aspects such as self-centring behaviour, peak deformation levels, and the components responsible for energy dissipation.

A significant rocking mechanism was observed under earthquake excitations. The use of a carefully designed arrangement of connections, including rocking, roller, and pin connections, effectively channeled the inertia force from the roof mass to the braces without creating any moments at the connections even under significant seismic excitations. This design approach ensured that the beams and columns remained undamaged during all seismic tests. The braces, in turn, efficiently dissipated the seismic energy through stable and ductile plastic deformation, as shown in Figure 6. Drift ratio time-history plots are shown in Figure 7. Despite peak drift ratios reaching approximately 2.5% in the tests, no collapse of the structure was observed. Most importantly, the maximum residual drift ratio was approximately 0.06%, well below the residual drift limit of 0.2% specified by Sullivan et al (2009) and the tolerance for 'as-built' imperfection tolerances in design specified in EN-1090-2 (CEN, 2008). These results proved that the combination of rocking connections and post-tensioned strands within the PT system demonstrated excellent self-centring behaviour. More information on the shake table test results can be found in Goggins et al. (2020), McCready et al. (2020) and Goggins et al. (2021).

At the conclusion of each test series, the braces were easily replaceable, highlighting the ability of the SC-CBF to reduce downtime and lower repair costs. Moreover, due to its robust self-centring behaviour, the SC-CBF can help avoid demolition costs resulting from excessive residual displacement. Under a variety of earthquake records, the SC-CBF system has repeatedly demonstrated its expected dynamic response behaviour, returning to its vertical position after large earthquakes, effectively dissipating seismic energy from the earthquake, and protecting the non-dissipative structural elements (beams, columns, and post-tensioned strands).

Figure 6: Plastic deformation of the bracing members under shake table excitation. (Goggins et al. 2021)

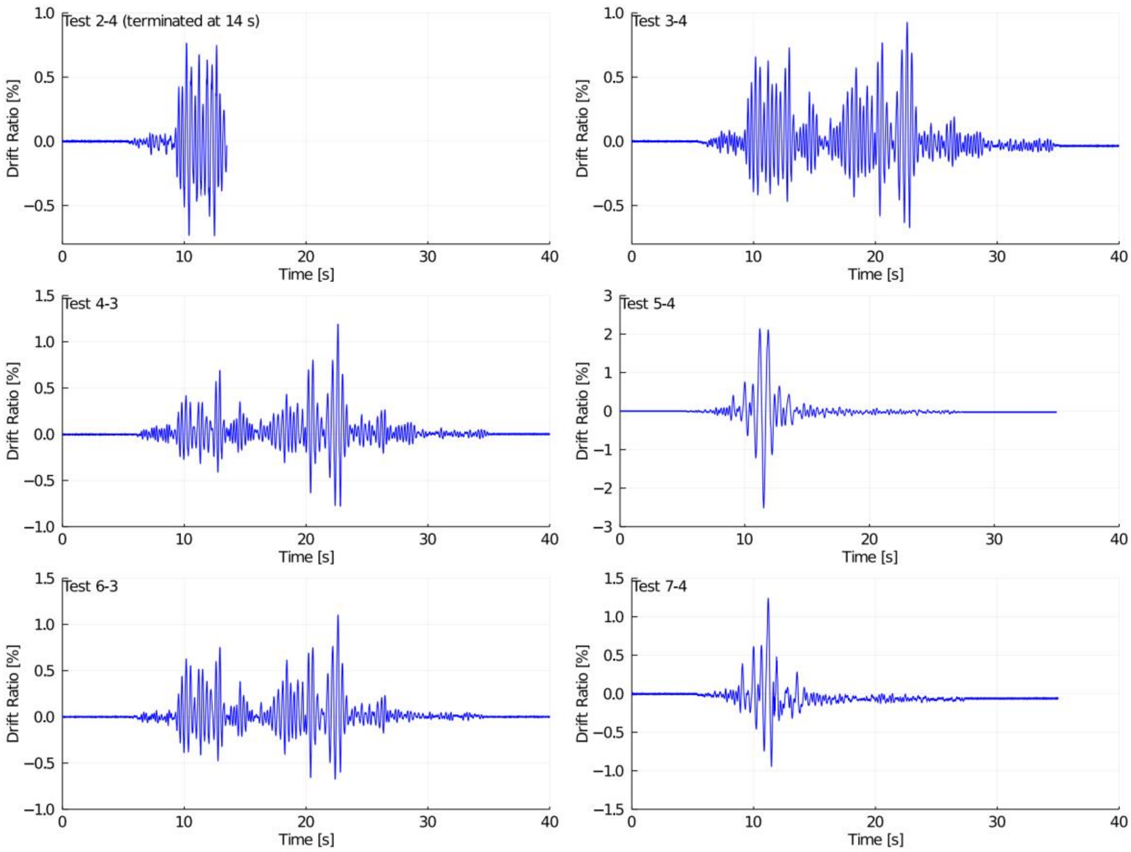

Figure 7: Drift ratio time-history plots for the largest ground motion applied in each test series. (Goggins et al. 2021).

3.3. Numerical Model Validation

To effectively validate the developed numerical model for the SC-CBF frame, numerical analyses were performed and the results compared with the shake table test results data. The shake table accelerations actually imposed in each test were employed in the OpenSees numerical simulations. Drift ratio time-histories from the test data and numerical simulations are compared in Figure 8. As can be observed, the numerical models consistently predicted zero residual drift ratios, successfully capturing the self-centring behaviour displayed by the SC-CBF in the experimental tests.

The drift ratios show good agreement between the numerical predictions and experimental observations, with an average difference of around 17%, which is acceptable given the complex nonlinear dynamic behaviour conditions. For example, in terms of the maximum drift ratios observed during the shaking table tests, the selected tests recorded values of 0.76% and 1.07% in the OpenSees simulations, with a maximum absolute difference between experimental and numerical values of approximately 28%. Notably, Test 45 exhibited the most reliable and smallest differences between the presented experimental and numerical models in Figure 8, with a drift ratio of around 0.93% and a maximum absolute difference of approximately 10%. Drift ratio time history curves of this form are particularly useful in assessing lateral deformation demands during seismic activity.

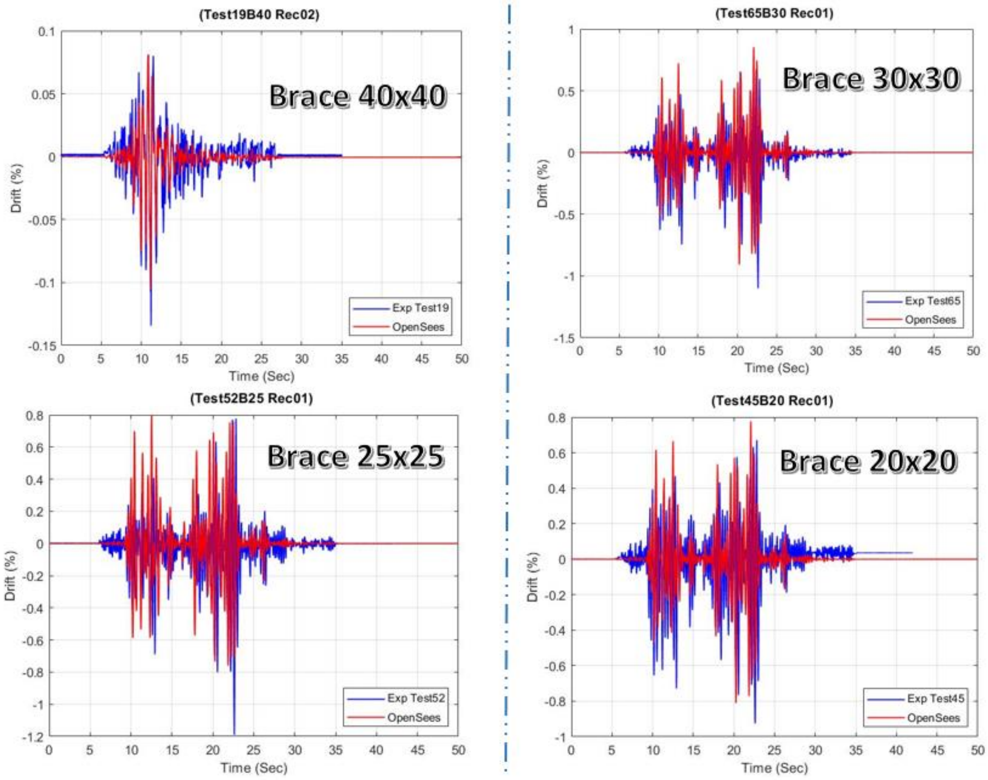

Figure 8: The comparison of inter-storey drift ratios for different brace sections involves both numerical analysis and experimental measurements.

4. Summary and Future Works

This paper presents a series of research assessments that were performed to develop a novel self-centring concentrically braced frame (SC-CBF) system. This system achieved self-centring behaviour by combining rocking connections and post-tensioning strands. The concentrically braced members were strategically designed to dissipate energy through plastic deformation. The pushover tests confirmed the effectiveness of the post-tensioning system, which worked in conjunction with bracing members that experienced buckling under cyclic axial loading, while other structural elements remained protected.

Through detailed experimental studies, in terms of cyclic pushover loading and shake table excitation, the performance of the proposed SC-CBF system was validated. The results of the experimental observations revealed several key conclusions. The incorporation of the rocking connection in the design of the SC-CBF effectively protected the structural elements, notably preventing damage to beams and columns during seismic events, with the majority of the seismic energy dissipated by the braces. The combination of post-tensioned strands and rocking connections resulted in exceptional self-centring behaviour, eliminating residual drifts even under substantial peak inter-storey drift demands. Additionally, the ease with which damaged brace members could be replaced between experiments highlights the resilience of the system and its ability to fully restore functionality after experiencing significant earthquake loading and displacement demands. These findings collectively emphasize the SC-CBF's promising performance in terms of structural protection, self-centring capabilities, and repairability, positioning it as a valuable option for seismic-resistant structural design.

In addition to the experimental studies, a numerical model was constructed using OpenSees, drawing from existing research on modelling concentrically braced frames and post-tensioning systems. These individual components were integrated to form a comprehensive model of the entire SC-CBF system. The comparative analysis served as a validation mechanism, affirming the effectiveness of the numerical model in predicting the behaviour of the SC-CBF structure. The numerical model closely matched the observed behaviour of the physical SC-CBF structure across various aspects, including drift ratios, self-centring behaviour, and fundamental periods. This validation reinforces the appropriateness of the model for conducting further in-depth investigations into the design and behaviour of SC-CBFs.

The combination of dynamic models and experimental tests opens up opportunities for conducting more extensive and detailed studies, particularly in the context of multi-storey SC-CBF structures subjected to earthquake loading. The integration of dynamic modelling capabilities provides a platform for in-depth exploration of the seismic performance of SC-CBFs, enabling researchers to develop deeper investigation into their responses and behaviour under dynamic earthquake conditions.

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