Performance validation of a self-centring steel structure using robust data sets from shake table testing

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ABSTRACT: In recent years, there has been a shift in seismic design from moment-resisting frames to concentrically braced frames (CBFs) due to their simpler construction and cheaper costs. CBFs resist the actions created in seismic events through energy dissipation in the form of plastic deformations in braces. This paper analyses the performance of a novel self-centring CBF (SC-CBF) which aims to reduce inter-storey drifts and residual deformations in a structure. The main novelty of this structure is its self-centring behaviour, through the use of post-tensioned (PT) strands running parallel to the beam members anchored to the exterior flange of columns. The system works upon the principle of closing gap openings which open at joints between beams and columns due to the ground motion. The tension forces provided by the PT strands can close the gap openings and return the structure to its vertical position, while energy is dissipated through the plastic deformation of the bracing members. Results from shake table testing, conducted in the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in R. North Macedonia which imposed lateral accelerations, are used to analyse the performance of this novel SC-CBF system. Different data sets, namely the brace middle span strain, roof acceleration and brace elongation, are compared for selecting the robust data sets that can be used to understand the performance of the system. This is achieved by comparing the structure lateral forces calculated from the three data sets. The self-centring behaviour of the designed SC-CBF is also verified by analysing the inter-storey drifts.

KEY WORDS: Concentrically braced frame; self-centring; energy dissipation; seismic loads; test specimens; lateral deformation.

1 INTRODUCTION

Seismic activity poses a real threat to life and economic activities of many countries around the world. The number of people living in seismically active regions today stands at 2.7 billion, around one-third of the global population [1]. Existing earthquake protective technology for structures can be classified as passive, active and hybrid systems. As the most widely used system, the passive system can further be classified as Tuned Mass Dampers, Hysteretic Dampers, Seismic Isolation and Energy Dissipation systems, with energy dissipation systems the most widely used. In recent years, there has been an increase in the application of concentrically braced frames (CBFs), a type of energy dissipation system. Based on the past earthquake events, it was found that the failures of many historic CBFs have been as a result of lateral deformations [2], revealing that the structural damage is directly related to the lateral deformation. Hence, drift limits are placed on structures to conform to the damage limitation requirement. Recently, many research works were focusing on improving the seismic performance of traditional CBFs, mainly to limit the peak lateral displacements [3-13]. For controlling the structure residual deformation after the earthquake event, the self-centring system is a possible solution. A US-Japan research programme looked into precast concrete construction and Precast Seismic Structural Systems (PRESSSS) found that the post-tensioned (PT) system at connections not only provided moment resistance but also generated a restoring force taking the structure back to its original position [14]. Thus, a self-centring concentrically braced frame (SC-CBF), which introduces the self-centring behaviour to the conventional CBFs, was proposed [15-17]. The SC-CBF system works upon the principle of a rocking mechanism which opens at joints between beams and columns, which avoids the potential beam and column damage caused by earthquakes. Thus, all the imposed earthquake energy is dissipated through the plastic deformation of the bracing members. With PT strands installed along the beams, the gap openings can be closed and the structure can return to its vertical position. In this paper, the concept of SC-CBF is described. The shake table tests, aiming to evaluate the seismic performance of a full-scale SC-CBF structure, are described. A methodology is proposed to evaluate the feasibility of the recorded data sets as confirmation of data accuracy is crucial when evaluating the structural performance of the frame. Data accuracy can be lost due to sensor failure or data may be impaired due to their fixing to the test frame visible as background noise in data sets. The proposed method is applied to analyse four test results, to validate the concept of this new type of earthquake protective structure.

2 METHODOLOGY

2.1 Concept of SC-CBF

Figure 1 shows a single-storey SC-CBF with two members concentrically braced. Different from the conventional CBF, the SC-CBF employs the rocking connections to fix the beams to the columns and the columns are pinned to the ground. The rocking connection enables the beam to rock against the flanges of the column. Thus, there is no moment forming at the beam and column ends. Through the rocking mechanism, the beams and columns of the SC-CBF can be protected from being damaged. As the rocking connection does not provide the
lateral stiffness to the frame, the PT strands are used to strength the frame in the lateral direction. Under the earthquake loading, the frame is laterally deformed, which opens the gap of the rocking connection and elongates the PT strands. Hence, the strands can provide self-centring forces to the frame to close the connection gaps and consequently, position the frame back to the vertical position. As the rocking connection and the post-tensioned strands are designed to behave elastically under earthquake loading, the bracing members are employed in the SC-CBF as the energy-dissipating components. The braces not only provide lateral stiffness to the structure, but also dissipate the imposed earthquake energy through forms of plastic deformations. After the earthquake event, the only components needed to be replaced are the braces as the rest structural members are protected by the rocking connections. The self-centring behaviour can minimise the influences of the residual displacements on the structure and thus, reduce the structure downtime and the repairing costs.

Figure 1. Concept of SC-CBF (adapted from O'Reilly [17]).

2.2 **Shake Table Tests**

To validate the seismic performance of this innovative structure, a full-scale SC-CBF was designed, manufactured and tested on a shake table under real earthquake events. The SC-CBF structure, designed by the National University of Ireland, Galway, was modified and extended based on the SC-CBF tested carried out by O’Reilly [17]. The test structure was constructed of one SC-CBF and two external frames. Figure 2 shows the schematic of the middle frame, which is the SC-CBF. As can be seen, the SC-CBF was different from the one in Figure 1. There were additional beams introduced to hold the braces, aiming to avoid the direct interaction between the braces and the beam/column members. The additional beams were connected to the column flanges via the rocking connections. There were two pairs of post-tensioned strands run through the beam centre line, to provide the self-centring forces. To avoid the local failure caused by the rocking mechanism, the beams and columns were strengthened by steel plates and stiffeners in the connection zones. The middle column was connected to the roof and the table via pinned connections, while the two external columns were fixed by slotted connections. Regarding the two external frames, their beams and columns were pin connected. It means that the two external frames can support part of the roof weight but cannot provide the lateral stiffness to the testing structure. There were mass blocks (about 20 tonnes) mounted on the roof. The three frames were placed on the shake table in parallel and were connected through steel beams and braces to make them share the same lateral deformation under earthquake loading. This can ensure that the inertial force of the roof mass is efficiently transferred to the middle frame shown in Figure 2, which is the SC-CBF. Under earthquake loading, the SC-CBF supplied the lateral resistance to the structure and dissipated the earthquake energy via the brace plastic deformations.

There were a series of shake table tests, with four types of SHS brace installed, conducted in the Institute of Earthquake Engineering and Engineering Seismology (IZIIS). In this research, four experimental tests were selected and validated based on the methodology proposed in section 2.3.

![Figure 2. SC-CBF Test setup (a).](image-url)

(a) Test frame

![Figure 2. SC-CBF Test setup (b).](image-url)

(b) Accelerometer locations

![Figure 2. SC-CBF Test setup (c).](image-url)

(c) Displacement transducer and load cell locations
Table 1 lists the details of the four tests, where the testing structure was exposed to the ground motion recorded selected from the Duzce-1999 earthquake (M7.3), under different scale factors. These tests can be grouped into two pairs according to the brace types. In the first two tests, the SHS 25x25x2.5 braces were installed and tested. In Test 1, a relatively small scale factor was applied to make the structure vibrate elastically, while in Test 2, a relatively large earthquake was imposed to the structure to approach the brace failures (the same braces were used in Test 1 and Test 2). Tests 3 and 4 were carried out following the same testing method.

To monitor the structural behaviour of the SC-CBF, instrumentations (e.g. accelerometers, strain gauges, displacement transducers, etc.) were installed. There were accelerometers attached to monitor the acceleration at roof level. For each brace, four strain gauges were installed on its mid length. Besides the strain gauges, the brace elongations were measured by the linear variable displacement transducers (LVDTs) and an accelerometer recorded lateral acceleration at roof level. The recorded data set was used to validate the performance of the SC-CBF via the methodology described in the following section.

2.3 Validation Methodology

Due to the rocking mechanism, the roof mass inertial force can only be resisted by the lateral forces provided by the braces, according to the force equilibrium. Thus, to verify the data accuracy and to establish a full understanding of the system behaviour under seismic loads, the lateral forces provided by the braces can be compared with the inertial force of the roof mass.

The lateral forces provided by the braces can be calculated from the brace strain data. The average strain ($\varepsilon_{br}$) captured by the four strain gauges mounted on the brace middle span was used. According to the constitutive law of the uniaxial material, the brace axial force ($F_{br}$) can be calculated by equation (1). It should be noted that this expression is only applicable for estimating brace force in the elastic phase.

$$F_{br} = E\varepsilon_{br}A_{br}$$

(1)

where $E$ is the Young’s Modulus of the steel and $A_{br}$ is the cross-section area of the brace.

The lateral force ($F_{br,lat}$) given by the two braces can be derived by equation (2).

$$F_{br,lat} = F_{br,r} \cos \theta - F_{br,l} \cos \theta$$

(2)

where $F_{br,l}$ and $F_{br,r}$ are the axial forces of the left and right braces, respectively; $\theta$ is the brace angle, which equals to 36.3°.

The obtained lateral force, $F_{br,lat}$, is compared with the roof mass inertial force ($F_{mass,lat}$), which is calculated using the accelerometer data (equation (3)).

$$F_{mass,lat} = ma$$

(3)

where $m$ is the roof mass and $a$ is the roof acceleration recorded by the accelerometer.

It should be highlighted that due to the existence of the damping, the two lateral forces cannot be perfectly matched in theory.

Alternatively, the brace elongation data recorded by the LVDTs can be used to provide an estimate of average strains in the brace members. Thus, the brace force estimated from the strain gauge data was compared to the brace force calculated from the LVDT data. By comparing the lateral forces calculated from the three data sets, not only can the fundamental behaviour of the SC-CBF be proved, but also can the reliability of each instrumentation be verified.

Another critical feature of the SC-CBF is the self-centring behaviour. In this study, the self-centring behaviour of the novel SC-CBF was established by finding the residual inter-storey drift, which is obtained from the displacement data recorded by the linear potentiometers (LPs).

3 RESULTS AND DISCUSSION

3.1 Lateral Force

Figure 3 compares the left brace axial forces calculated according to the strain gauge and LVDT data of Tests 1 and 3, where the bracing members behaved elastically. Theoretically, the two lateral forces should equal, so a linear fit trend line (solid black line) is presented in each plot. As the brace elongations of the two tests were relatively small, relatively good correlations (indicated by the black solid line) can be found between the two lateral forces. However, the lateral forces calculated based on the brace elongation data are significantly lower than that from the strain data.

For Tests 2 and 4, there is almost no correlation found between the two brace axial forces, as shown in Figure 4. The weak correlation is mainly due to the yielding and buckling of the braces, which were observed during testing.

The results comparisons between the LVDT and strain data reveal that at least one of the two instrument types was not reliable during testing.

The lateral forces given by the strains are compared with the roof inertial force. As can be seen in Figure 5, the two lateral forces match well. It demonstrates that the designed SC-CBF behaved as the theoretical expectations, namely only the bracing members will provide lateral resistance to the lateral forces. Moreover, it proves the captured strain and acceleration data are reliable as the two lateral forces agreed well.
Conversely, it indicates the LVDT data failed to represent the elongation of the braces accurately. Figure 6 compares the lateral forces from Tests 2 and 4. It can be observed that when time is less than 8 s, the lateral forces have a relatively good agreement with each other compared to the rest of data. With the time increased, the horizontal brace forces started to shift from the inertia forces. This is caused by the buckling and yielding of the bracing members (Figure 7) as the testing frame was exposed to a relatively high PGAs. Hence, the equation (1) is no longer applicable when the test specimen enters the plasticity phase. Overall, it could be concluded that the SC-CBF behaved as expected and the data sets provided by the accelerometers and strain gauges were reliable. The presence of brace buckling failure also indicates the energy generated from the seismic loading was dissipated by the braces, which agrees well with the desired structural performance.

3.2 Residual Drifts

To verify the self-centring behaviour of the testing structure, the inter-storey drifts of the four tests were analysed, based on the displacement data provided by the two LPs installed parallel to the additional beams. Figure 8 shows the drift data of Tests 2 and 4. In the two tests, the maximum inter-storey drifts are around 16~17mm, which caused significant brace plastic deformations members (Figure 7). However, the residual drifts of the two tests are around zero, demonstrating the good self-centring performance of the SC-CBF, which is benefited from the post-tensioned strands. This conclusion can be further demonstrated by the residual drift data summarised in Table 2, where all the four residual drifts are less than 0.6 mm.
4 CONCLUSIONS

In this study, the experimental data was utilised to validate the feasibility of the instrumentations and to evaluate the performance of the SC-CBF structures. By comparing the lateral forces calculated from the three data sets (namely the LVDT, strain gauge and the acceleration), it was found that the lateral force obtained from the strain data agreed well with that from the acceleration data. This not only demonstrates the good reliability of the measured strain and acceleration data, but also proves the excellent feasibility of the energy dissipation method utilised by the SC-CBF.

However, by performing the studies on the correlation between the brace elongation data and the brace mid length strain data, the LVDTs were found to constantly underestimate the brace deformation. This suggests the presence of error in the measurement capability of the LVDT sensors. It may be due to some level of sensor failure. For this reason, the experimental data from the strain gauges are preferred to analyse the performance of the brace specimens.

The performance of the novel SC-CBF as a self-centring system, evaluated in terms of the inter-storey drifts, is good since the residual drifts for the four tests were less than 0.6 mm. These negligible lateral drifts guarantee that the SC-CBF structure had returned to its original position at the end of each test. By using the performance validation method, the selection of robust data sets was possible allowing it to demonstrated that the seismic loads were transmitted to the brace specimens efficiently which make the braces the only member of the SC-CBF dissipating energy.

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