Development of a Novel Self-Centering Concentrically Braced Frame System for Deployment in Seismically Active Regions

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ABSTRACT: Conventional concentrically braced frames (CBFs) undergo many cycles of inelastic deformation during seismic excitation. This inelastic deformation leads to the possibility that after a significant seismic event, the structure will remain in an out of plumb position, even if the system has performed exactly as required by current design codes. This paper presents an improved braced framing system that eliminates such residual deformations of the structure by using a post-tensioning arrangement that will ensure the structure self-centres following an earthquake. This is achieved by combining the bilinear elastic response of the post-tensioning frame with the inelastic behaviour of the tubular steel bracing members to give a system that both dissipates hysteretic energy and ensures self-centering behaviour. The mechanics of the system are first presented along with some simple expressions of the frames behaviour, followed by the development of a numerical model that captures the behaviour of such a system. The results from the numerical model indicate that this self-centering concentrically braced frame (SC-CBF) is capable of undergoing many cycles of inelastic deformation whilst ensuring recentering behaviour. Using this numerical modelling, further analysis can be performed for larger structures using this novel self-centering technology.

KEY WORDS: Braced steel frames; Earthquake engineering; Numerical modelling; Seismic loading; Self-centering.

1 INTRODUCTION

During the design basis earthquake (DBE), most seismic resisting systems are expected to undergo many cycles of inelastic deformation to dissipate energy during a seismic event. For concentrically braced frame (CBF) systems, the dissipating mechanism is the diagonal bracing members, which often consist of steel tubular bracings. These tubular bracings are expected to exhibit inelastic behaviour through tensile yielding and global inelastic buckling. This means that under the DBE, the structure is expected to significantly yield, which can result in large residual deformations throughout the structure. Following an earthquake, these residual deformations can be extremely problematic considering the difficulties associated with attempting to straighten a building that has experienced permanent lateral inter-storey displacements (or drifts) of, for example, 2.5%, which is within codified limits. Furthermore, residual drifts can also reduce the performance of some structural systems during earthquakes.

McCormick et al. [1] conducted a study on residual drifts in structures following earthquakes and concluded that residual drifts greater than 0.5% are perceivable by occupants. It was concluded that in Japan, it was generally cheaper to rebuild the structure rather than attempting to repair if residual drifts present in the structure exceeded this amount. This demonstrates that residual deformations require consideration during the design process. Attempts have been made by Erochko et al [2] to estimate the residual drifts in a structure following the DBE and how to incorporate these into the initial design process. An alternative approach has been to develop systems that inherently re-center following seismic events. These systems have been called self-centering systems and have been present in seismic design since the construction of the bridge over the South Rangitikei bridge in New Zealand in 1981.

Major development in self-centering systems was completed during the early 1990's through the PRESSS initiative, where self-centering concrete frame and wall systems were developed by use of unbonded post-tensioning (PT) to combine the dissipative behaviour of the concrete system with the elastic restoring force of the PT arrangement to give the 'flag-shaped' hysteresis loop (Figure 1.). This concept has been extensively developed for concrete [3, 4], steel [5, 6, 7, 8] and timber systems [9] for use in seismic zones. The focus of this paper is to introduce a new self-centering concentrically braced frame (CBF) that exhibits self-centering behaviour through a PT arrangement and dissipates hysteretic energy through inelastic yielding and buckling of the tubular bracing members. The general arrangement and behaviour is first described followed by the development of a numerical model to demonstrate the behaviour under cyclic loading and how self-centering behaviour is always achieved under numerous cycles of inelastic deformation.

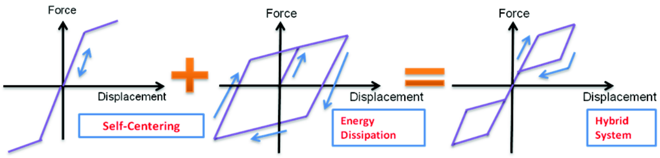

Figure 1. Flag Shaped Hysteresis Loop.

2 SELF-CENTERING SYSTEMS

2.1 Introduction

Numerous self-centering systems have been developed in earthquake engineering since the inception of the PRESSS program to apply the PT technology to systems to give self-centering behaviour. One of the principle ways to achieve this self-centering is through gaps opening during loading in areas such as wall-floor interface [10], or in the beam-column interface [6, 7, 8, 9], where the gap opening is forced closed by the post-tensioned cables that act across the connection to give self centering, while the structure deformation causing this gap opening also causes the inelastic behaviour of the dissipative system. For steel systems, the most common method of post-tensioning has been to post-tension the beam column connection, where different systems differ by the means to which they dissipate energy, as the PT arrangement must remain elastic to achieve self-centering. Many of these systems [6, 7, 20] are adaptations of the traditional moment resisting frame system, while [8] uses shear plate wall system to dissipate energy.

2.2 Self-Centering Concentrically Braced Frame (SC-CBF)

This paper presents a new system for CBF similar to the aforementioned self-centering systems that combine the rocking beam-column connection with a dissipative mechanism, where for this SC-CBF system, the diagonal bracings are the dissipating elements. Figure 2 shows the general arrangement of the system, which consists of a 2 bay CBF that has an additional PT element added to the beams and is anchored at the columns to re-center the system. The hysteretic behaviour of this SC-CBF is shown in Figure where it can be seen that the combined hysteresis of both the braces and the PT elements gives the flag-shaped hysteresis described earlier.

The self-centering behaviour of the SC-CBF primarily depends on the compressive resistance of the brace, where if more slender braces are used, the brace buckles quite early and the level of PT required to ensure that the force at point 5 in Figure is greater than zero is less than that what would be required if a more stocky brace was used and the compressive resistance was higher. Another key feature of the SC-CBF is the connection detail of the gusset plates, where traditionally gusset plates are connected using either welds or bolts to both beam and column.

By connecting the gusset plates to both beam and column in the SC-CBF, this would result in a restraint on the rocking behaviour of the beam column connection, which is paramount to the self centering behaviour of SC-CBF. To avoid this, a longer bay width may be used to result in the use of gusset plates connected only to the beam and not the column. Ongoing experimental testing and numerical modelling at NUI Galway [11] for the behaviour and design of these beam only gusset plate connections is being conducted, so the design and detailing of these gusset plates is not discussed here.

Another feature of using wider bay braced frames is that the effective length of the brace increases, therefore increasing its slenderness and decreasing its compressive buckling load, which has already been deemed to be advantageous in SC-CBFs as the level of PT required is reduced with increased slenderness.

3 SC-CBF HYSTERETIC PROPERTIES

This section describes the construction of the hysteretic response of the SC-CBF shown in Figure 3, by examining the response of the individual contributions. First the force-deformation relationship for the braces is examined, followed by the initial frame response before decompression of the rocking connection and the post-decompression stiffness of the system.

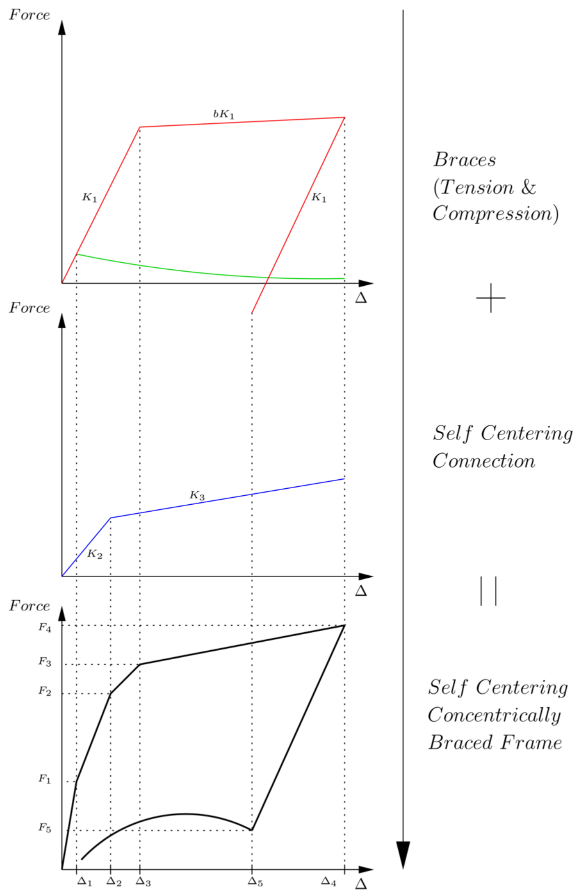

Figure 3. Combined hysteretic response of the SC-CBF.

3.1 Brace Response

For a frame similar to that in Figure 2, but with no PT arrangement and only simple connections, the quantities K_1 and Δ_1 can be determined. The initial lateral stiffness K_1 can be derived to be the following:

$$K_1 = \frac{A_{br} E B^2}{L^3} \quad (1)$$

where A_{br} is the area of the tension brace, E is the Young's Modulus, B is the bay width and L is the length of the brace member. The corresponding displacement Δ_3 at which the braces yield in the frame is given by:

$$\Delta_3 = \frac{f_y L^2}{BE} \quad (2)$$

where f_y is the yield strength of the steel tubular member. The contribution of the compression brace to the response of the frame is a function of the brace slenderness. In addition to this, during seismic loading, the braces will have undergone many cycles of tensile yielding and inelastic buckling. The

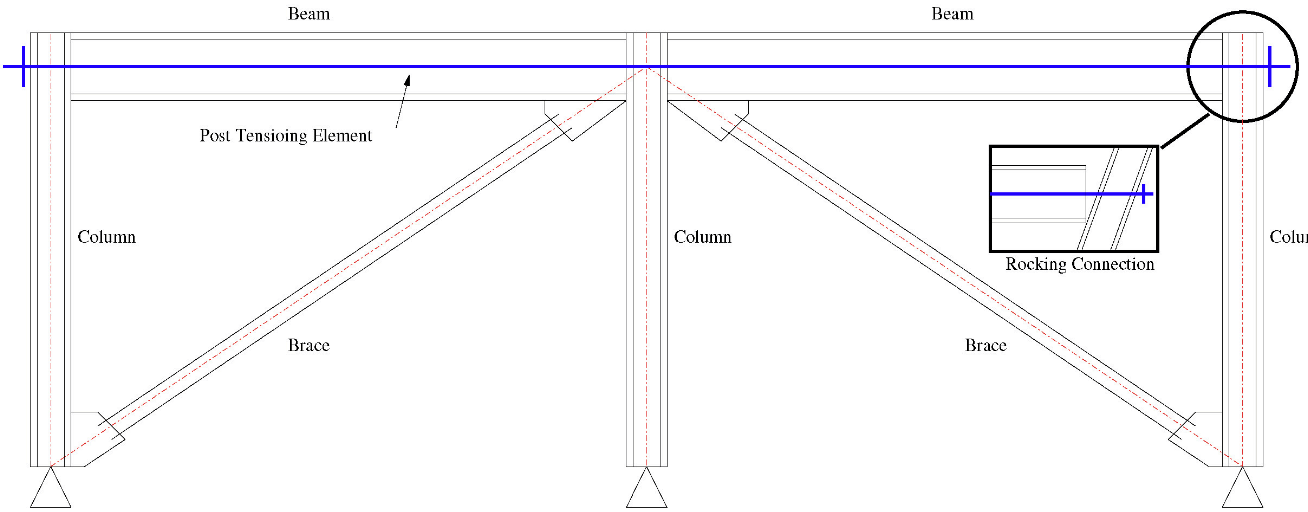

Figure 2. General arrangement of SC-CBF.

buckling load may be determined using the Euler buckling formula, but during inelastic buckling cycles the actual resistance is significantly less. The contribution of the buckled brace has been experimentally investigated by many [12, 13, 14, 15] with equations developed that are a functions of both displacement ductility and brace slenderness. For example, Wijesundara [14] suggested that 25% of the buckling load of the brace be considered in the response of the frame, while Goggins [12] suggested 33% of the brace buckling capacity be included up until a non-dimensional slenderness ($\bar{\lambda}$) of 2.4, with no contribution being added for higher slenderness values. This is an important factor in the design of SC-CBFs where it is necessary to ensure that the inelastic buckling capacity is less than restoring force being provided by the post-tensioned connection.

3.2 *Rocking frame response*

Prior to decompression, the SC-CBF without any bracing members will behave as a moment frame, so the initial stiffness K_2 can be determined using the principle of virtual work. For the frame in Figure 2, this can be determined as:

$$K_2 = \left[\frac{H^3}{8EI_C} + \frac{H^2 B}{24EI_B} \right]^{-1} \tag{3}$$

where H is the height of the frame and I_C and I_B are the second moment of area of the column and beams respectively. The corresponding displacement at which the response of the frame changes to post decompression stiffness depends on the level of PT applied to the frame and the depth of the beam. The compressing moment given by an initial PT force P_{T0} on a beam with height b_h is given by:

$$M_c = P_{T0} \frac{b_h}{2} \tag{4}$$

Assuming that the four connections will develop similar moments simultaneously at decompression, then:

$$4M_c = K_2 \Delta_2 H \tag{5}$$

which can then be rearranged to give and expression for the roof displacement at which decompression occurs:

$$\Delta_2 = \frac{2P_{T0} b_h}{K_2 H} \tag{6}$$

Following decompression, the stiffness of the frame depends on the forces generated in the PT elements as the gap opening at the rocking at the connection results in an increase in the PT force P_T. Christopoulos [21] derived an expression for the increase in PT forces due to the gap opening and expansion of the frame. Using this derivation, the increase in PT force as function of relative rotation at the connection θ can be expressed as

$$P_T = P_{T0} + 2K_{PT}\left(1 - \frac{1}{\Omega}\right) b_h \theta \tag{7}$$

where Ω is given by:

$$\Omega = 1 + \frac{K_b}{(K_c + 2K_{PT})} \tag{8}$$

and K_B, K_C and K_{PT} are the stiffness's of the beam, column and PT elements, respectively. This can then be arranged to give an expression for the post decompression stiffness K_3 as follows:

$$K_3 = 4K_{PT}\left(1 - \frac{1}{\Omega}\right) \frac{b_h^2}{H^2} \tag{9}$$

4 NUMERICAL MODELLING OF SC-CBF

A numerical model for the SC-CBF has been developed that captures the behaviour of both the rocking frame and the braced frame. The model is developed using OpenSees [16], which is an object oriented open source framework. Numerous publications are available [14, 17, 18] on how to accurately capture the behaviour of tubular bracing members subjected to cyclic loading. These models have been calibrated against numerous experimental test results for validation and are used herein as the modelling parameters for the bracing members in the SC-CBF.

The rocking frame is a relatively new concept in steel systems and has been in use for various steel self-centering systems [6, 7, 8]. The modelling of this has been discussed by Christopoulos and Filiatrault [19], where they developed a model consisting of a bilinear elastic rotational spring to represent the rocking behaviour of the connection. A more realistic approach that has been used by many researchers [6, 7, 8] is to use a series of contact springs and rigid links to represent the rocking of the beam against the column during cyclic loading. Figure 4 shows the basic arrangement, where the rigid links are used to represent the face of the column and also the face of the end of the beam. Using as series of contact springs, the rocking of the connection can be modelled. Further details on this connection model that accounts for beam depth can be found in [20]. Figure 5 shows the complete model used for the SC-CBF, where the bracing members are connected to the beams, as for beam-only gusset plate connections. This modelling procedure has been verified against existing experimental data by [6, 7], where the post-tensioned rocking connection was tested under cyclic loading. Using the modelling procedure discussed here for the rocking connection, these experimental results were closely replicated numerically using OpenSees, therefore validating this approach to modelling the rocking connection, and hence is used for the modelling of the SC-CBF.

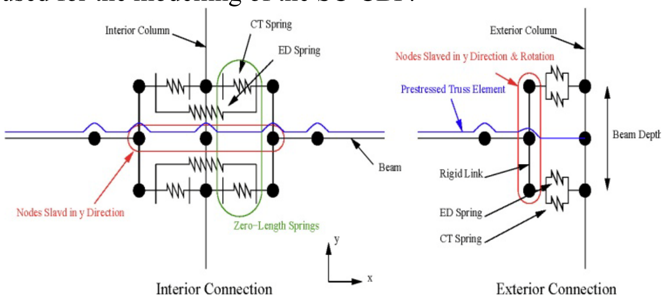

Figure 4. PT connection accounting for beam depth (Adapted from [19]).

5 CYCLIC LOADING

Using the numerical model previously discussed, a simple single-storey frame is examined to observe the behaviour of the SC-CBF under cyclic loading. An example SC-CBF similar to Figure 2 using *HE320A* members for the columns, *IPE600* members for the beams, *100x100x8-SHS*-S275 braces and two no. 30*mm* diameter cables with a initial PT force of 500*kN* is analysed by cycling it through a series of cycles corresponding to 0.5, 1, 2, 3 and 4% interstorey drift. The results of this simulation are shown in Figure 6, where it can be seen that the flag-shaped hysteresis is achieved through the combination of the PT and the brace response. It is evident that the relatively low contribution of the brace in compression is advantageous in terms of achieving the flag-shaped loop. This bracing used here corresponds to a non-dimensional slenderness ($\overline{\lambda}$) of 1.92, assuming an effective length factor of 0.9, which is a more slender brace than what would typically be used in CBFs. Also shown in Figure 6 is a plot of the expressions developed in Equations (1) to (9), where it can be seen that these expressions produces hysteretic loops that closely matches those of the numerical simulation using Opensees.

6 CONCLUSIONS

A new arrangement for CBFs has been introduced where PT elements were used to provide a bilinear elastic restoring force to the system during cyclic inelastic loading of the braced frame. It has been shown how the response of the single storey SC-CBF is that of a flag shaped hysteresis loop. Thus, during seismic loading, the occurrence of residual interstorey drifts due to inelastic behaviour of the bracing members will be prevented. A numerical model of the SC-CBF was developed where this flag shaped hysteresis was observed using modeling procedures that have been extensively examined for traditional CBFs, and also experimental data to validate the use of the rocking connection model. From these results, this new SC-CBF system can be further developed into a new seismic resisting system with superior overall performance of traditional CBFs.

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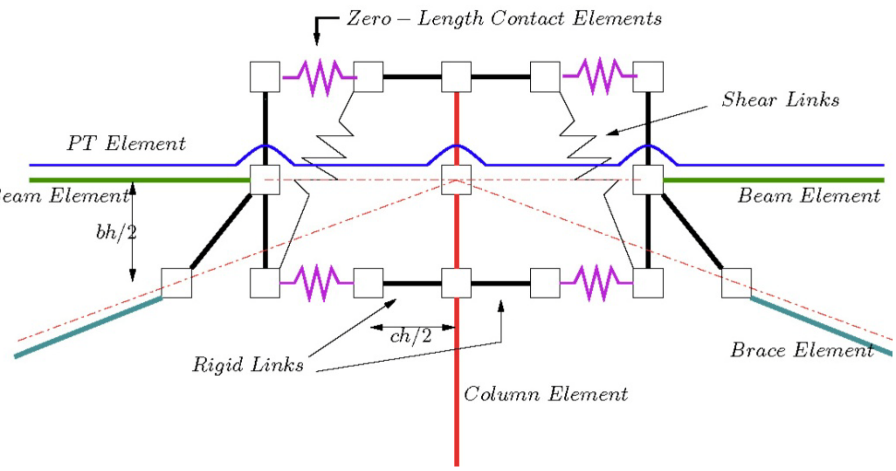

Figure 5. SC-CBF model arrangement.

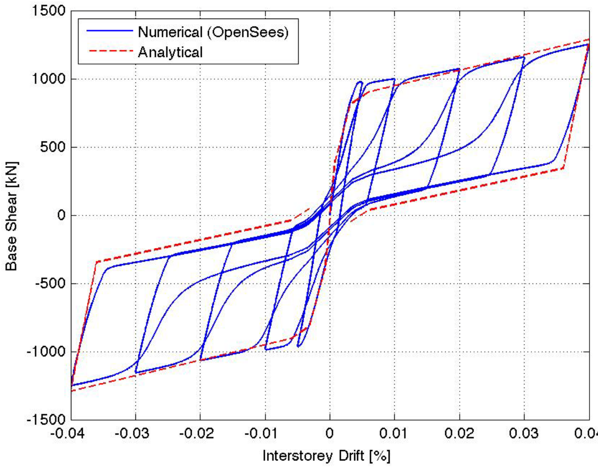

Figure 6. Force-deformation of 1-Storey SC-CBF.

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