Experimental validation of Rocking CBFs with Double Acting Ring Springs

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ABSTRACT: Double acting ring springs are an energy dissipation device developed for Centralised Rocking Concentrically Braced Frames (CRCBFs). Two configurations have been experimentally tested with both giving good behaviour but the second configuration, known as Type II, exhibiting the better performance, developing stable and repeatable flag-shaped hysteresis loops with considerable energy dissipation and active self-centring. To observe the global behaviour of the CRCBFs, two-thirds scale bottom storey frames with the double acting ring spring type II were tested. Each bottom storey frame comprised a beam, a brace, a concrete filled SHS column with a double acting ring spring at the column base, a central rocking pivot base plate, and a vertical post. The beam and brace were passed through the concrete filled SHS column to achieve rigid connections between those components. A vertical post was provided to support the beam and to maintain the stability of the frame, as only a half part of the braced frame was fabricated.

The experimental testing of bottom storey frames has been conducted under slow-speed static cyclic loading and to high-speed dynamic loading. Furthermore, the bottom storey frames have been modelled in SAP2000. The experimental test results showed the behaviour of the double acting ring spring governed the global behaviour of the CRCBFs which developed stable and repeatable flag-shaped hysteresis loops under different loading rates and always dependably self-centred. Additionally, the experimental test results were in accordance with the SAP2000 results.

1 INTRODUCTION

A rocking system featuring a central rocking pivot and energy dissipation devices has been developed for Concentrically Braced Frames (CBFs), as shown in Figure 1a. CBFs are designated for the superstructure of this rocking system because of their high strength and stiffness to resist lateral loads (Bruneau, Uang, and Sabelli 2011). This rocking system is designed to rotate about the centre of the CBF, which halves the magnitude of vertical movement at the CBF corners, lessening the vertical displacements of the sides of the frame under lateral loading and hence causing less displacement compatibility issues with the attached floor slabs. Thus, the system requires a double acting system to dissipate earthquake energy and to accommodate upward and downward movements at the edges of the CBF during Ultimate Limit State (ULS) earthquakes. It is also required to be very stiff under Serviceability Limit State (SLS) earthquakes and under ULS wind loads. Ringfeder®, a compression only ring spring comprising inner and outer rings that contact each other through steeply inclined contact surfaces (Fig. 1b), is suitable for the rocking system as the springs can be arranged to work as a double acting system and be partially prestressed, to produce a high initial stiffness up to a defined force level, thus meeting the rigidity requirement under SLS earthquakes or ULS wind loads.

To work as a double acting system, a greased ring spring with end plates at both ends is placed inside a flanged steel cartridge with a base plate. A machined down threaded rod is centrally passed through the ring spring and top end plate and then the rod is fastened to connect between a column base plate located on the top of the ring spring cartridge and a bottom end plate. Then, the ring spring is prestressed to 50% of its capacity by fastening it using a clamping plate which is bolted to the flanges of the cartridge (Fig. 1c). The column base plate with two short SHS supports is allowed to uplift. This

system generates a flag-shaped hysteresis curve, as shown in Figure 1d. The force capacity of the ring spring can be doubled by adding another cartridge in parallel. In a greater than SLS earthquake, the column base plate either moves downward, compressing the ring spring through the top end plate or moves upward lifting up the bottom end plate and the rod compressing the ring spring. Energy is dissipated through this process and the superstructure is designed for the maximum compression force from the ring springs so as to remain elastic. After a design level earthquake, the double acting system provides a return force to make a structure back to initial position without post-earthquake structural damage and the structure is expected to be fully operational. In the event of maximum considered earthquake (MCE), the rod and the column base plate are designed to yield after the ring spring reaches lock-up in tension and compression respectively, and detailed for replacement if required.
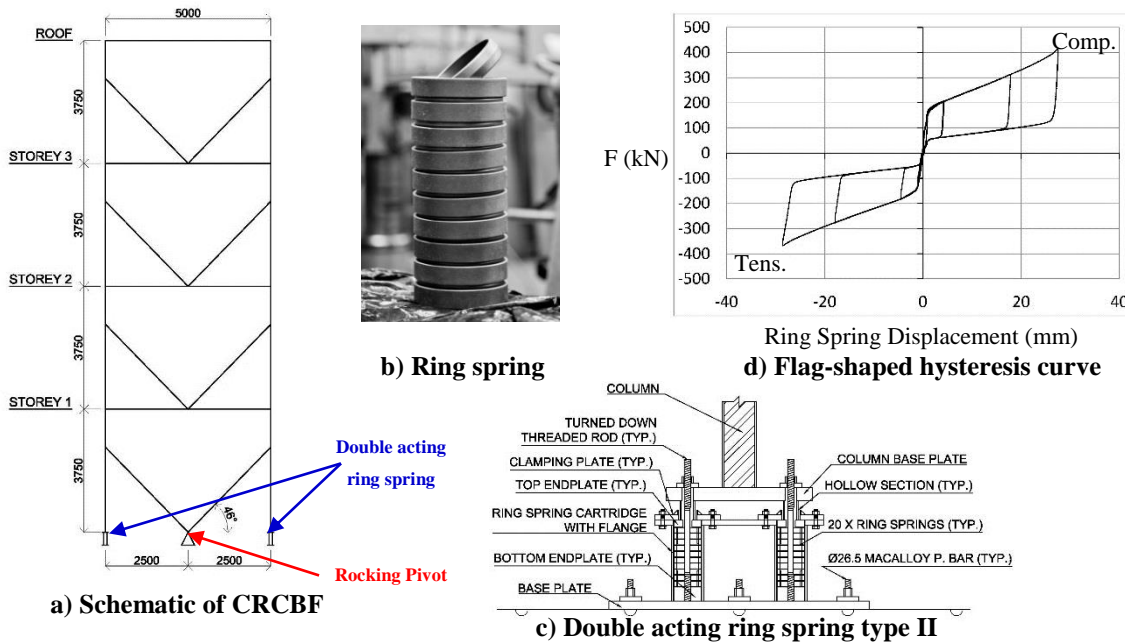

a) Schematic of CRCBF

b) Ring spring

d) Flag-shaped hysteresis curve

c) Double acting ring spring type II

Figure 1. Centralised Rocking Concentrically Braced Frame (CRCBF) system

2 MODELLING OF PROTOTYPE BUILDING IN SAP2000

A four-storey office building prototype has been modelled in SAP2000 v18.2.0 for a conceptual design and detailing requirements. The building used Centralised Rocking Concentrically Braced Frames (CRCBF) system as the primary lateral resisting system and was located in Wellington with a shallow soil (Class C). The structural plan area was 71m by 21m and the floor height for each storey was 3.75m. CRCBFs are placed at the perimeter frames and designed as one direction lateral resisting system. Double acting ring springs are defined as Link/Support, a damper – Friction Spring property. The ring springs are assigned at the bottom of CF-SHS columns as a non-linear property with active direction at both directions. The CRCBF members are given in Table 1. The three-dimensional model and the CRCBF are shown in Figure 2.

Table 1. CRCBF members

Storey	Beam (CB)	Brace (BR)	Column (mm)
4	200UC59.5	310UC118	
3	310UC118	350WC197	Concrete filled SHS500x500x16
2	310UC118	331SWC218	$f^{'}_c$=50MPa
1	310UC118	350WC230	

Notes: Steel Grade of Beam and Brace is G300; Steel Grade of Column is C450L0

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a) 3D Model   **b) CRCBF**

Figure 2. Prototype building with CRCBFs

This building was analysed using time history with four selected earthquake records (i.e. El Centro 1940, Hokkaido 2003, La Union 1985, and Lucerne 1992) which have been scaled according to NZS1170.5 Clause 5.5. The first storey displacements obtained from those analyses were used for the displacements inputs of bottom storey CRCBF dynamic testing. As the global behaviours of the building between those earthquakes are similar, only El Centro 1940 earthquake record and the building behaviour (base shear vs. roof displacement) of that earthquake are presented in this paper, as shown in Figure 3.

a) Scaled El Centro 1940 earthquake record (PGA: 0.38G)   **b) Hysteresis loops**

Figure 3. Time history analysis input and output

3   EXPERIMENTAL TESTING OF THE BOTTOM STOREY CRCBF

3.1   Test description

Experimental testing of the bottom storey CRCBF has been conducted to validate the concept and numerical analyses of CRCBF system. The objectives of this testing were; 1) to observe the CRCBF hysteresis loops, 2) the self-centring capability, and 3) the behaviour of the centrally rocking pivot, 4) the double acting ring spring in the frame, and 5) the beam/brace/column connection under slow-speed static cyclic testing and dynamic testing with the high speed testing at earthquake rates of deformation. The static cyclic and dynamic loading protocols that were applied to the bottom storey CRCBF are shown in Figure 4.

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a) Uniform cyclic loading at 0.5mmps

b) Cyclic loading at 20mmps

c) El Centro 1940 eq record (PGA: 0.38G)

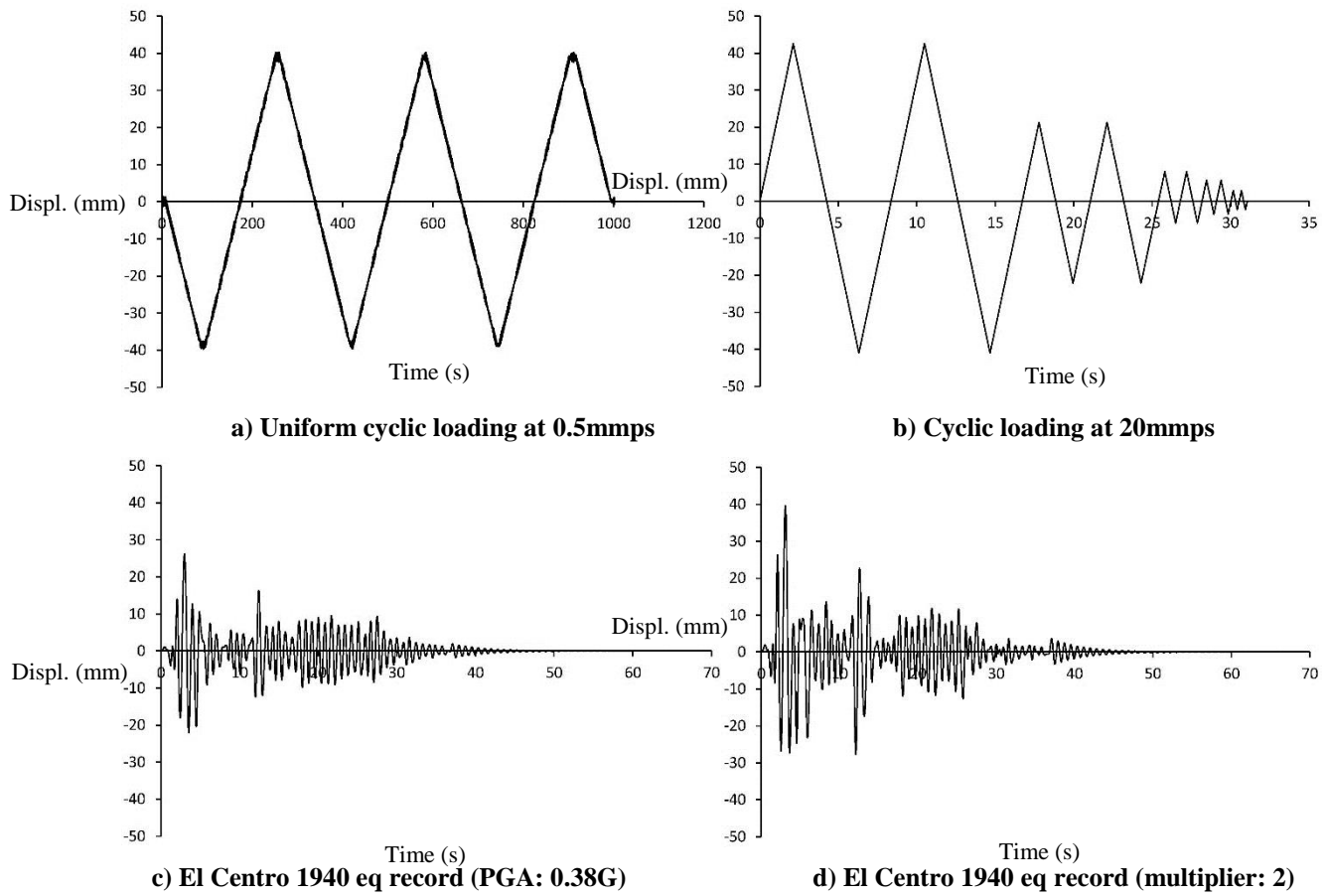d) El Centro 1940 eq record (multiplier: 2)

Figure 4. Static cyclic loading and dynamic loading of the bottom storey CRCBF

3.2 Test setup

A two-thirds scale bottom storey CRCBF comprised a beam, a brace, a concrete filled SHS column, a double acting ring spring type II at the column base, a central rocking pivot base plate, and a vertical post. The beam and brace were passed through the SHS column and simple fillet welded to the external face of the SHS column (Fig. 5). Afterwards, the SHS column was filled with high strength concrete to enable compression strut transfer to operate within the concrete core. This fabricating method was developed to achieve simple and practical rigid connections between those three components. A vertical post was provided to support the beam and maintain the stability of the frame, as only a half part of the brace frame was fabricated. The component details are given in Table 2.

a) Right side of SHS   b) Left side of SHS   c) Inside SHS before filled with concrete
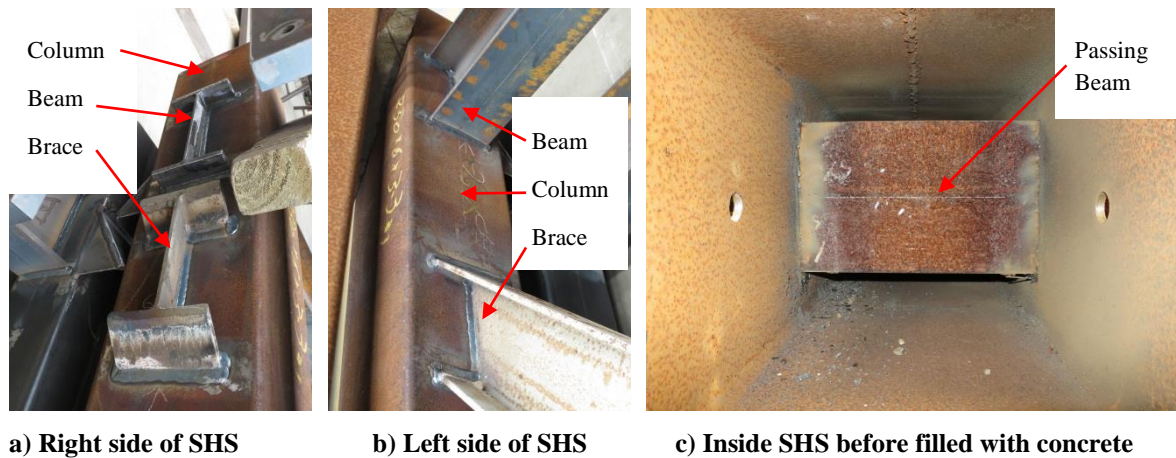
Figure 5. Fabricating beam/brace/column connection

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Table 2. Components of bottom storey CRCBF testing

Components	Dimensions (mm)	Quantity
Ring springs	Type 12400	2 x (19+2 half ring)
Machined down plain class 8.8 threaded rod	Threaded region ⌀30; plain region ⌀24 L = 650	2
Ring spring cartridge	-	1 set
Vertical post (C450L0)	SHS 200x200x5; L = 2338	1
Concrete filled column* with column base plate and two SHS supports (C450L0)	SHS 250x250x6; L = 2209	1
Beam (G300)	250UB37.3; L = 2110	1
Brace (G300)	150UC30.0; L = 2522	1
Rocking pivot base plate (G300)	1200x700x50	1
AISI 4140 cylinder (Pin joint)	⌀50	1

*) f'_c = 50MPa

The fabricated bottom storey CRCBF (white frame in Fig. 6) was placed on the rocking pivot base plate pinned with the AISI 4140 cylinder and the ring spring cartridge. The column base plate was connected to ring spring cartridge through the two SHS supports and the machined down threaded rods but it was allowed to uplift. A secondary tall column and channel pair were provided to guard and minimise the out-of-plane movement of the bottom storey CRCBF during testing. During cyclic loading, the frame was forced to rotate back and forth on the rocking pivot base plate permitting the column and its base plate to move upward and downward transferring the axial forces to the foundation. In compression, the axial force was transferred directly from the column to the foundation through the ring springs while, in tension, the axial force was transferred through the ring springs, the machined down threaded rods, the ring spring cartridge, and the base plate. At the same time, the base shear was transferred to the foundation through the central rocking pivot.
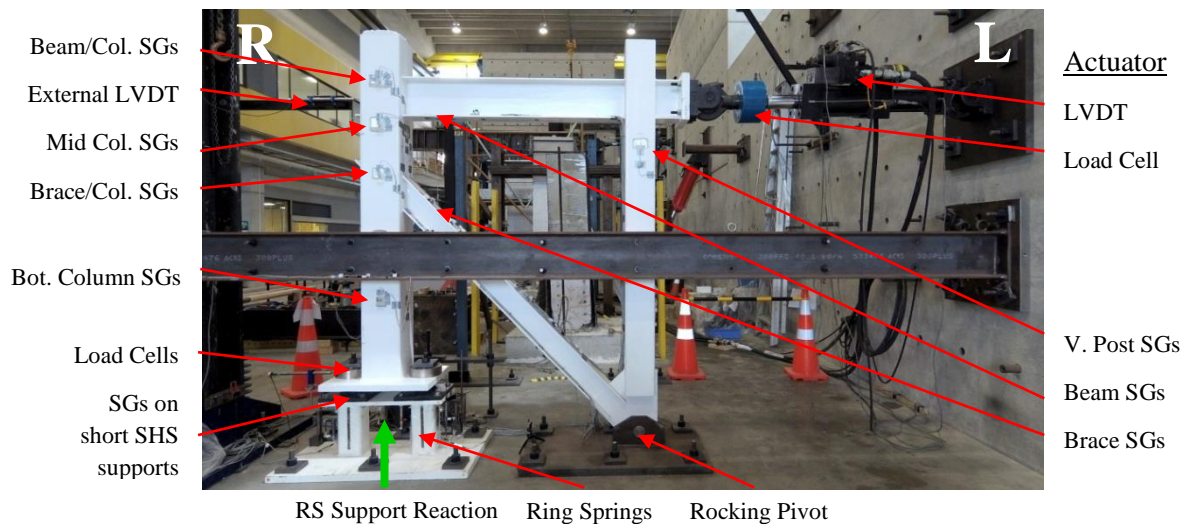
Figure 6. Bottom storey CRCBF test setup

The actuator which was connected to CRCBF from left side of the frame (Fig. 6) had built-in load cell and Linear Variable Displacement Transducer (LVDT) to measure horizontal force and displacement respectively. In addition, an external LVDT was provided on the right end of the frame to measure horizontal displacement of the CRCBF. The other three LVDTs were placed vertically on the column base plate to measure the vertical movements of the column base plate and the ring springs. Two string

potentiometers (String pots) were used to measure out-of-plane displacement. Strain gauges (SG) including rosette gauges were attached on the beam, brace, column, and vertical post to measure the internal forces. Strain gauges attached on the two short SHS supports of the column base plate measured the vertical compressive force when the frame was in compression. Two load cells were provided on the top of the column base plate to measure the vertical tensile force when the column base plate lifted up due to the frame in tension.

3.3 Test Results

The bottom storey CRCBF performed well when subjected to both slow-speed cyclic loading and high-speed dynamic loading showing stable and repeatable flag-shaped hysteresis loops. It also effectively self-centred at the end of each testing as indicated by the zero residual force in the actuator at the end of the testing when the frame had returned to zero displacement. The force to initiate the rocking was at 133kN and the maximum lateral displacement of the frame before the lock-up of the double acting ring spring type II was approximately 38mm or 1.52% drift. Both of them matched the bottom storey CRCBF analysis. The global behaviour of the CRCBF (Fig.7) was governed by the behaviour of double acting ring spring type II. However, Figure 7 showed a small bump occurred during compression in which the frame was tilting out-of-plane until the frame leaning on one side of the guard channels as the frame was restrained out-of-plane at mid height of the frame.
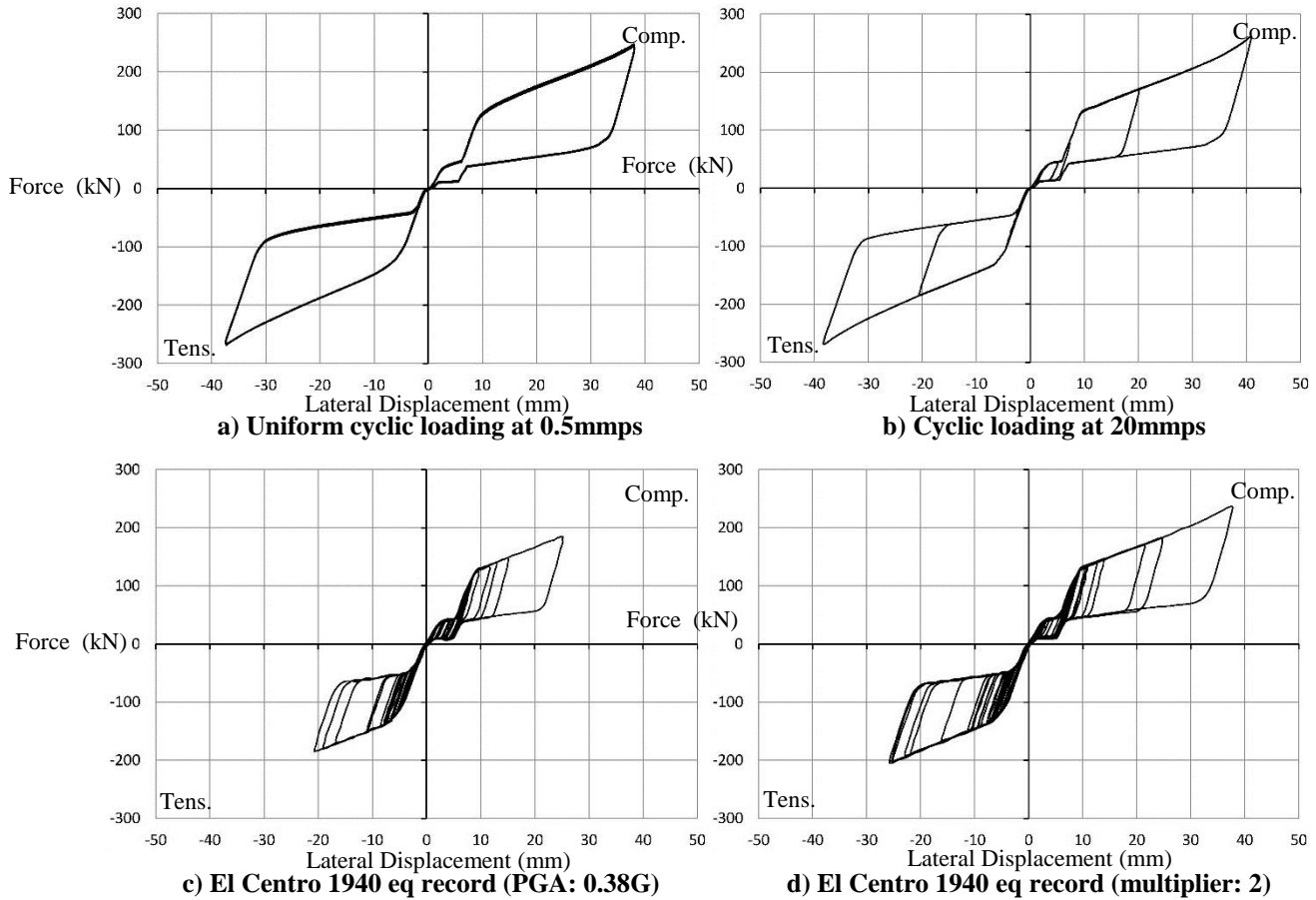

a) Uniform cyclic loading at 0.5mmps

b) Cyclic loading at 20mmps

c) El Centro 1940 eq record (PGA: 0.38G)

d) El Centro 1940 eq record (multiplier: 2)

Figure 7. Test results of static cyclic loading and dynamic loading of the bottom storey CRCBF

3.4 Numerical analyses in SAP2000

The bottom storey CRCBFs have been modelled in SAP2000 with members given in Table 2. The rocking pivot was modelled as a hinged support and the ring spring was modelled as a non-linear damper – Friction Spring acting in both compression and tension. The initial (Non-slipping) stiffness (k_0) was the stiffness of the ring spring when the ring spring was elastically stiff about 10,000 times of k_1 (CSI 2016). The slipping stiffness (Loading) was the ring spring loading stiffness (k_1) when the ring spring was elastically displaced and the slipping stiffness (Unloading) was the ring spring unloading stiffness (k_2) when the ring spring was recoiled about one-third of the loading force. The

pre-compression displacement was the displacement length to determine the initial force to initiate the elastic displacement of the ring spring. The stop displacement was the maximum displacement of the ring spring. The model was analysed using non-linear analysis. The two-dimensional model of the bottom storey CRCBFs and the axial forces acting in the member are shown in Figure 8.
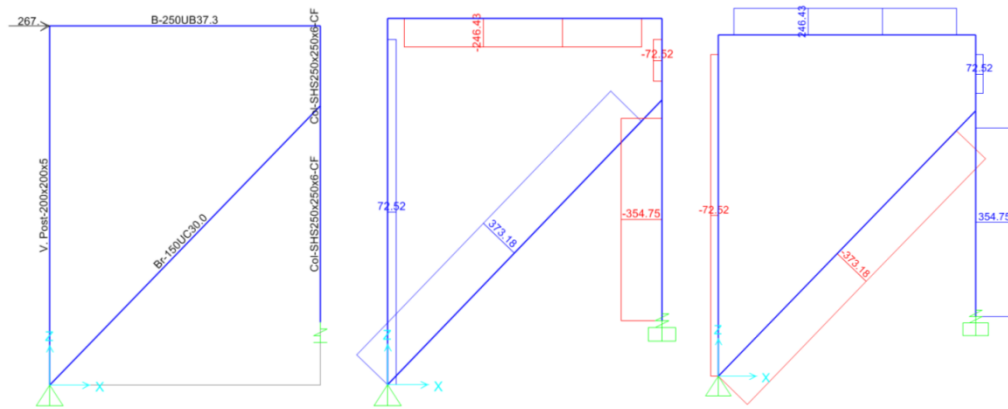
a) Members and applied loading in kN   b) Frame in compression   c) Frame in tension

Figure 8. Bottom storey CRCBFs model

4 COMPARISON BETWEEN TEST RESULTS AND NUMERICAL ANALYSES

The test results were compared with the numerical analyses results to verify the concept of CRCBF system in terms of the structure behaviour and internal forces. The CRCBF behaviour has been verified through the hysteresis response obtained from the experimental test results in Figure 7 which were in accordance with SAP2000 results in Figure 3. The axial forces between test results and SAP2000 results were compared in Table 4 with the locations of the measurements, as shown in Figure 6.

Table 4. Comparison of axial forces between test results and SAP2000 results

Axial Force		Compression			Tension		
At 267kN		Test Results	SAP Results	%	Test Results	SAP Results	%
Beam	kN	246	246	0%	-250	-246	-2%
Brace	kN	-372	-373	0.3%	363	373	3%
V. Post	kN	-59	-72	18%	40	72	44%
Bot. Col.	kN	179	355	50%	-324	-355	9%
RS reaction	kN	327	355	8%	-344	355	3%

Notes: Compression is (+); Tension is (-); all readings are from steel components.

During experimental testing, the column base described an arc as the frame rotated about the pin but the ring spring cartridge ensured the ring springs to operate in vertical direction minimising bending action to the ring springs and resisting only the axial forces from the column. The axial forces in the column were not distributed equally between the two stacks of the ring springs. In compression, the nearest ring spring from the rocking pivot was compressed earlier than the farthest ring spring. At the high compressive force, the farthest ring spring was compressed more than the nearest ring spring which was not able to be modelled in detail in SAP2000. The percentage differences of the reaction in ring springs in compression and tension were 8% and 3% respectively. Nevertheless, each ring spring behaved well and was able to resist the column axial forces as intended. The compressive force of the bottom column in the test results only represented steel SHS column. Hence, the approximate compressive force resisted by concrete column was obtained by subtracting the compressive forces of bottom column and RS reaction. The concrete contribution in the column in compression was significant transferring 45% of the total compressive force as opposed to in tension where the concrete only transferred 6% of the total tensile force.

5 CONCLUSIONS

The concept of a rocking system for use in CBFs has been verified by both testing and numerical analyses. The behaviour and hysteresis response of CRCBFs simulated in SAP2000 correlated well with the test results. The test results showed the behaviour of the double acting ring spring governed the global behaviour of the CRCBFs exhibiting stable and repeatable flag-shaped hysteresis loops. In addition, the consistency of the hysteresis loops generated from slow-speed static cyclic testing and high-speed dynamic testing proved the performance of the ring springs and CRCBF is independent to the loading rates. At the end of each testing, the CRCBF returned precisely to initial position without any structural damage and with no significant residual actuator force.

The axial forces between test results and SAP2000 results have been compared. The ring springs were not compressed uniformly due to the frame rotation, forming an arc and forcing the nearest ring spring from the rocking pivot to be compressed earlier than the farthest ring spring and at high compressive force, the farthest ring spring compressed more than the nearest ring spring.

A noticeable bump in the hysteresis response was caused by the frame tilting out-of-plane until the frame leaning on one side of the guard channels because lateral restraints were provided at the mid height of the frame which did not fully restrain the out-of-plane of the frame. Nevertheless, the stiffness and the flag-shaped hysteresis loops are always consistent in both compression and tension proving that the CRCBF system is working properly as intended in the concept.

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