The Rocking Steel Shear Wall Utilising Energy Dissipation Devices

by

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A final report submitted to

Earthquake Commission

Supervised by

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Notes

The original title is The Rocking Steel Shear Wall (RSSW) Utilising Energy Dissipation Devices. However, the title has changed from The RSSW Utilising Energy Dissipation Devices into The Centralised Rocking Concentrically Braced Frame (CRCBF) Utilising Energy Dissipation Devices. The rocking system requires a stiff super structure and, in this case, a Concentrically Braced Frame (CBF) is stiffer than a Steel Shear Wall (SSW). In addition, a modification in material properties is required to model SSW in software analysis. Due to this limitation, it is not feasible to perform dynamic analysis of RSSW. Nevertheless, the main component of this structure, which is the bottom storey frame, is not affected due to that super structure change.

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1. Introduction

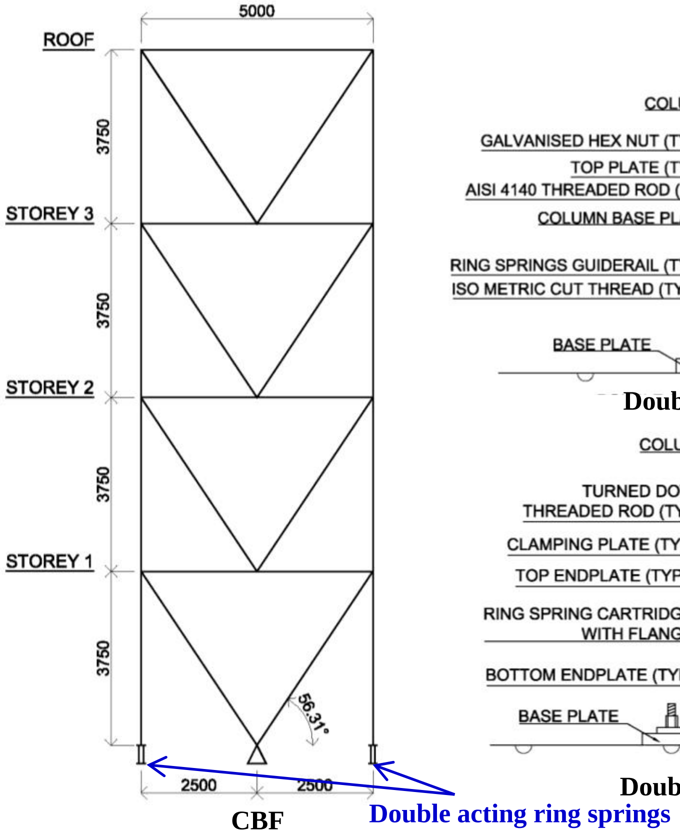
New Zealand is located in the ring of fire region where severe earthquakes frequently occur. Recent significant earthquakes were occurred in north-east of Te Araroa, North Island on 2nd of September 2016 with M7.1 and in Christchurch on 14th of February 2016 with M5.8. The 2010/2011 Canterbury earthquake series caused NZD 40 billion of damage. The August 2013 Grassmere earthquake caused significant damage in Wellington. Those events showed the needs of resilient structures.

In the severe 2010/2011 Canterbury Earthquake series, especially the two most intense earthquakes of that series, on 22nd February and 13th June 2011, steel structures designed for low ductility had minor damage and re-centred effectively. In contrast, more ductile structures were severely damaged and subjected to inelastic demand which necessitated detailed review and in some cases replacement of damaged components. There were only a few examples of steel structures that suffered more significant damage due to poor detailing or construction (MacRae and Clifton, 2013). Although some of damaged structures were successfully repaired, expensive structural repairs with the associated downtime caused business disruption and considerable economic loss.

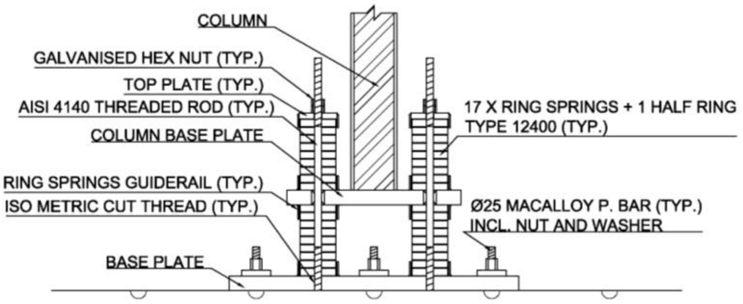
On the other hand, designing a traditional structure to remain elastic would be uneconomical in terms of costs and member sizes to provide the probability of infrequent severe earthquakes (Blume et al., 1961).

In order to keep a structure in the elastic range yet be cost-effective, the concept of a low damage design is introduced. Seismic resisting systems using this concept are expected to withstand severe earthquakes without major post-earthquake repairs, using isolating mechanisms or sacrificial systems that either do not need repair or are readily repairable or replaceable. Sliding friction connections, bolted replaceable link in an eccentrically braced frame, and post-tensioned rocking braced frames are the examples of the low damage design in steel buildings (SCNZ, 2014; Weibe, 2015).

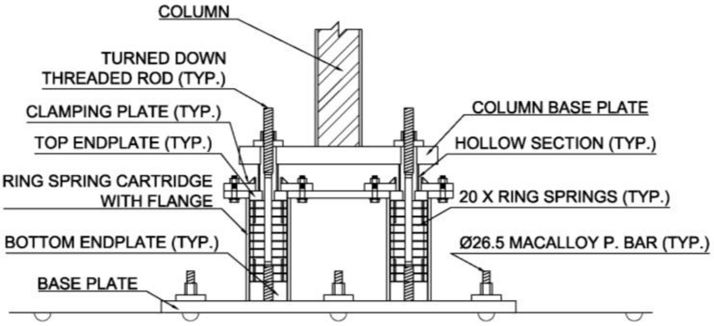
An innovative low damage design system named Centralised Rocking System with Energy Dissipation Devices for use in Concentrically Braced Frames (CBFs), as shown in Figure 1, is being developed. This system is intended to be stiff under gravity loading and minor earthquakes, remain essentially elastic under major earthquakes by undergoing controlled rocking, and actively self-centre following earthquakes. A centralised rocking pivot and V brace at the bottom storey of CBF permits CBF columns at the edges of the CBF to move upward and downward during earthquakes, with half the magnitude of vertical movement at the CBF columns for a given CBF rotation compared with a conventional rigid rocking wall, which rotates about the corners. Energy dissipation devices designed for the base of the columns not only dissipate considerable energy to minimise damage to the rest of the structure, but also provide restoring forces to pull the structural system back to the original position. The energy dissipation devices are double acting ring springs comprising Ringfeder®, a compression only friction ring spring, which is arranged to work as a double acting spring, as shown in Figure 1.



CBF



Double Acting Ring Spring Type I



Double Acting Ring Spring Type II

Figure 1: CBF with Rocking System and Double Acting Ring Springs Type I and II

2. Performance Objectives

A Centralised Rocking CBF system (CRCBF) is designed to resist gravity loading and lateral loading. Under gravity loading, the CRCBF is designed to carry all gravity loading into foundation system. Under lateral loading, the CRCBF has to meet specific performance requirements as follows:

1. **Serviceability Limit State earthquakes (SLS) and ULS wind**; the system is stiff under SLS earthquakes and ULS wind loads. The SLS event to NZS1170.5 has an 86.5% probability of exceedance in 50 years for a structure of normal importance (IL=2).

2. **Ultimate Limit State earthquakes (ULS)**; when the intensity of the seismic loads is greater than the SLS earthquakes, the structure is rocking and the energy dissipation devices are actively dissipating energy in order to keep the structure components elastic. The devices also provide self-centring following earthquakes. The ULS event to NZS 1170.5 has a 10% probability of exceedance in 50 years for a structure of normal importance.

3. **Maximum Considered Earthquake event (MCE)**; when the seismic loads exceed the ULS, selected components such as ring spring threaded rods and column base plates are expected to yield in tension and compression respectively. Other components remain elastic to prevent collapse or required extensive repair of the structure. The MCE event to NZS 1170.5 has a 2% probability of exceedance in 50 years for a structure of normal importance.

The annual rate of exceedance is obtained from Poisson Law as described in USGS website (earthquake.usgs.gov/hazards/about/basics.php)

3. Methodology

The following steps are being undertaken to produce a robust CRCBF design:

1. Developing rocking system concepts and preliminary design based on the expected performance of double acting ring spring at the column bases.
2. Implementing the two most suitable concepts to a prototype building (Appendix 1) to determine member and ring spring sizes for CRCBF.
3. Developing cost-effective designs and detailing requirements for the rocking system, the connections between beam, brace, and column.
4. Conducting Experimental testing to validate the concept, as follows:
5. Component testing
6. Double acting ring spring type I and type II testing
7. Bottom storey CRCBF testing (Rocking frame testing) with joint type I and type II

8. Observing the behaviour of the double acting ring springs and rocking frame. Refining the preliminary design based on the actual behaviour of the rocking frame.
9. Performing non-linear dynamic analysis of the CRCBF under El Centro 1940 and Hokkaido 2003 earthquake records and the outputs of the analysis are used for loading protocols for dynamic testing in rocking frame testing. These are chosen because their characteristics cover the range of earthquake ground motions expected (mix of near field and far field events).
10. Setting and modifying the performance targets so that the structural cost and performance are balanced.
11. Developing final design based and detailing requirements on the outputs of the experimental testing.

4. Double Acting Ring Spring Systems

As shown in Figure 1, The CRCBF system is designed to rotate about the central base of the CRCBF which allows the columns at the edges of the CRCBF to move upward and downward during earthquakes. Therefore, double acting ring spring systems are designed to control the rocking and provide self-centring under severe earthquakes. Two unique designs of double acting ring springs are proposed, as follows:

1. Double Acting Ring Spring Type I – Parallelogram Hysteresis Curves

   Two stacks of ring springs are assembled in series at top and bottom of a column base plate and prestressed to 50% of the spring capacity with a high tensile threaded rod connecting top plate to the foundation, as shown in Figure 1. The threaded rod is designed to yield after the top stack is locked up while the other components are designed to remain elastic. An exposed ring spring has to be encased with a protective casing to prevent the rings against dust, water, or other contaminants and also to preserve the grease. Also, guiderails are provided to keep the ring spring located in their position in plan. When prestressing two or more sets of ring springs, the prestressing must be applied simultaneously to both spring stacks to keep the prestressing force balance at each set.

   While the CRCBF is rocking, each stack operates in parallel. When the column is in compression, the bottom stack is compressed while the top stack relaxes and when the column is in tension, the top stack is compressed and it compressed the top plate and generates tensile force in the rod while the bottom stack relaxes. When the top spring is loaded, the bottom spring is unloaded, which cancels one-third of the initial prestressing force on both sides. Hence, this system generates a parallelogram hysteresis curve, as shown in Figure 2. This is not ideal for active self-centring.

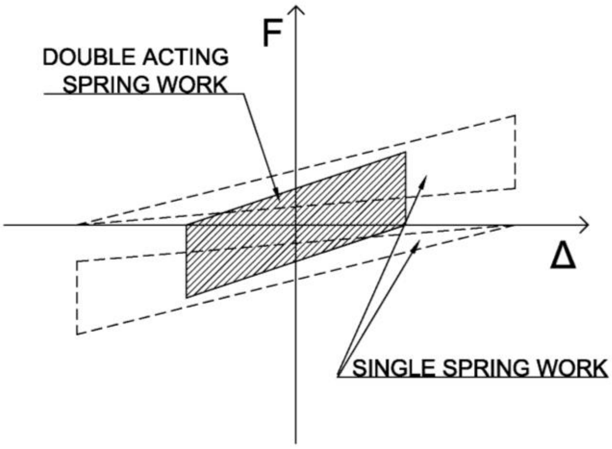


Figure 2: Parallelogram Hysteresis Curves

2. Double Acting Ring Spring Type II – Flag-Shaped Hysteresis Curves

   A greased ring spring stack with customised endplates at its both ends is put into a steel cartridge with a base plate. A machined to specified diameter high tensile threaded rod is centrally passed through the ring spring and endplates and is fastened to connect between a column base plate and a bottom endplate. Then, the cartridge is sealed by a clamping plate which is bolted to the flanges of the cartridge, as shown in Figure 3. The Double Acting Ring Spring Type II is shown in Figure 1.

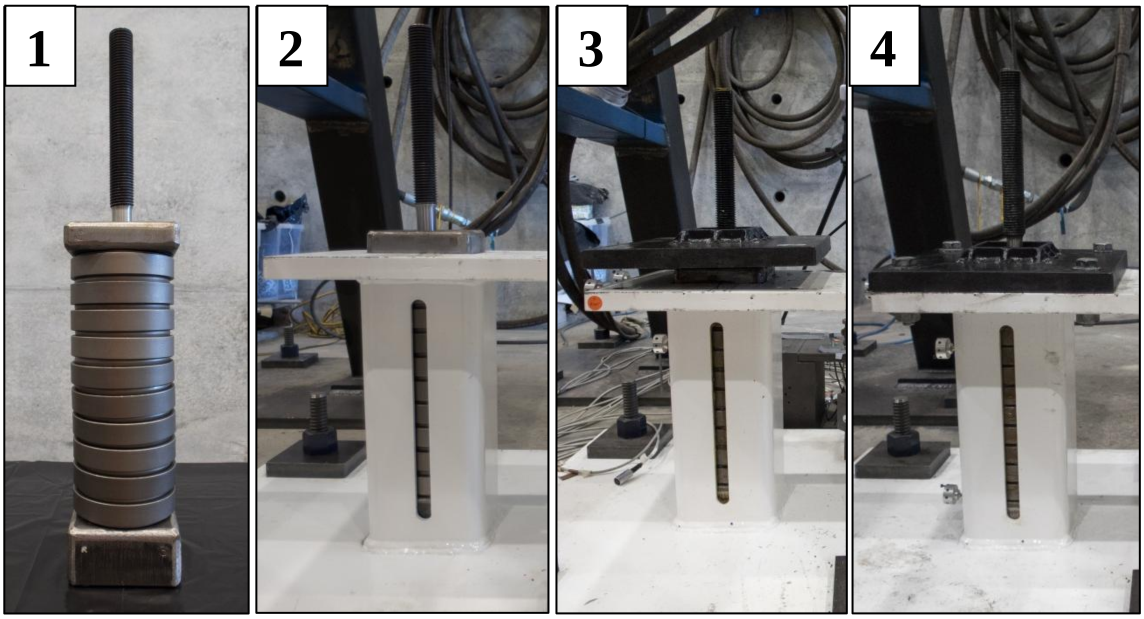


Figure 3: Double Acting Ring Spring Type II Assembly

The cartridge is used to secure the rings from dust, water, or other contaminants and also to protect the grease. A hollow section, which is a part a column base plate, transfers a compressive force to the top endplate but it is free to uplift. To ensure the spring is able to travel to the maximum spring travel, a sufficient gap has to be provided between a hollow section and a clamping plate and also between bottom end of a rod and cartridge base.

Taking an advantage of the linearity of the ring spring behaviour, the height of the cartridge is used to define the prestress force by measuring the spring displacement. For example, compressing the ring spring to 50% of the total spring travel represents a prestressed force level at 50% of the compression capacity. When the column is in compression, it compresses the top endplate and the spring. When the column is in tension, the threaded rod lifts the bottom endplate to compress the spring. This system generates a flag-shaped hysteresis curve and returns precisely to initial position as shown in Figure 4.

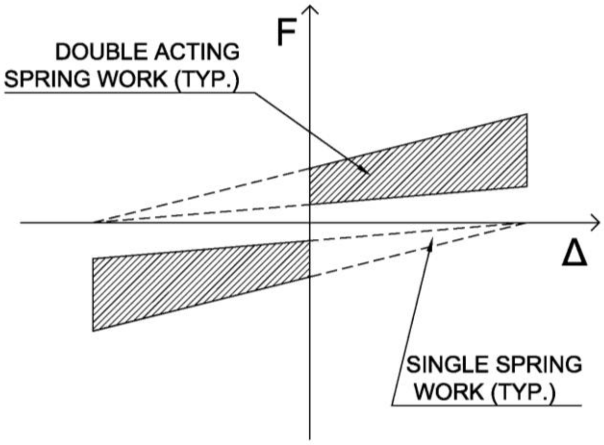


Figure 4: Flag-Shaped Hysteresis Curves

5. Experimental Testing

A series of experimental testing has been conducted to validate the concepts of rocking system. There are 3 (three) phases of experimental testing as follows:

1. Component Testing – Tensile Testing of Threaded Rods

   One of the important components of double acting ring spring is a machined down threaded rod. This rod is acting as a fuse which is allowed to yield after the ring spring is locked up. Therefore, tensile testing of threaded rods (Figure 5) has been conducted to check yield strength and tensile strength thoroughly.

Figure 5: Tensile Testing of a Threaded Rod

The testing was conducted on 29 September 2015 using Avery machine and has been completed with excellent results. In general, plain class 8.8 has at least 800MPa of ultimate strength and 640 MPa of yield strength. The testing results showed 866 MPa of ultimate strength and 660 MPa of yield strength which correspond to the plain class 8.8 mechanical properties. These values will determine the strength limit of the double acting ring spring systems in tension and the limit of lateral deformation of a structure. Figure 6 is one of the testing results of M30 threaded rod with M24 shank and Figure 7 is the yielded threaded rod.

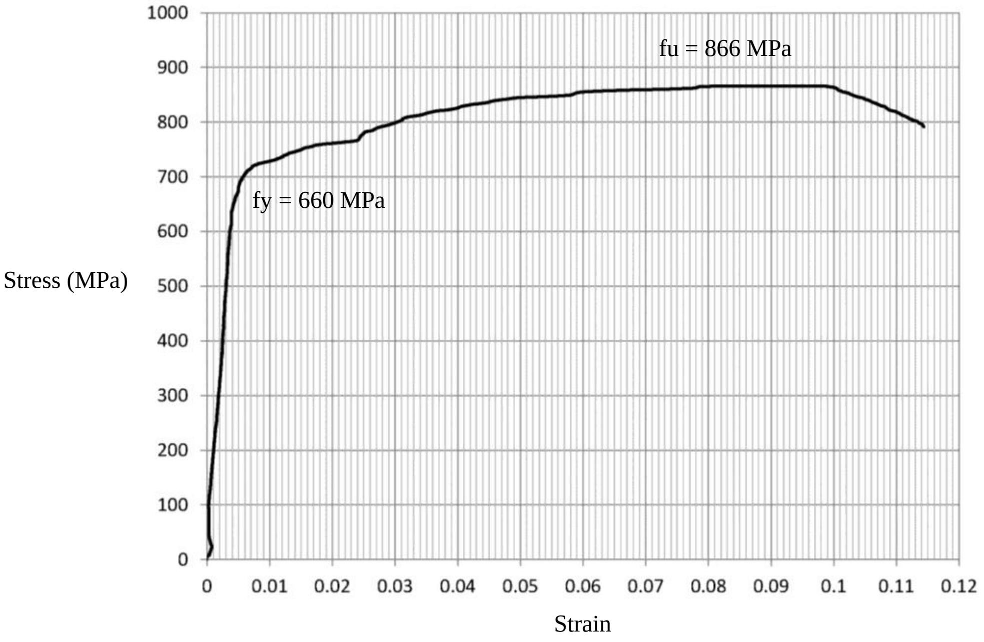


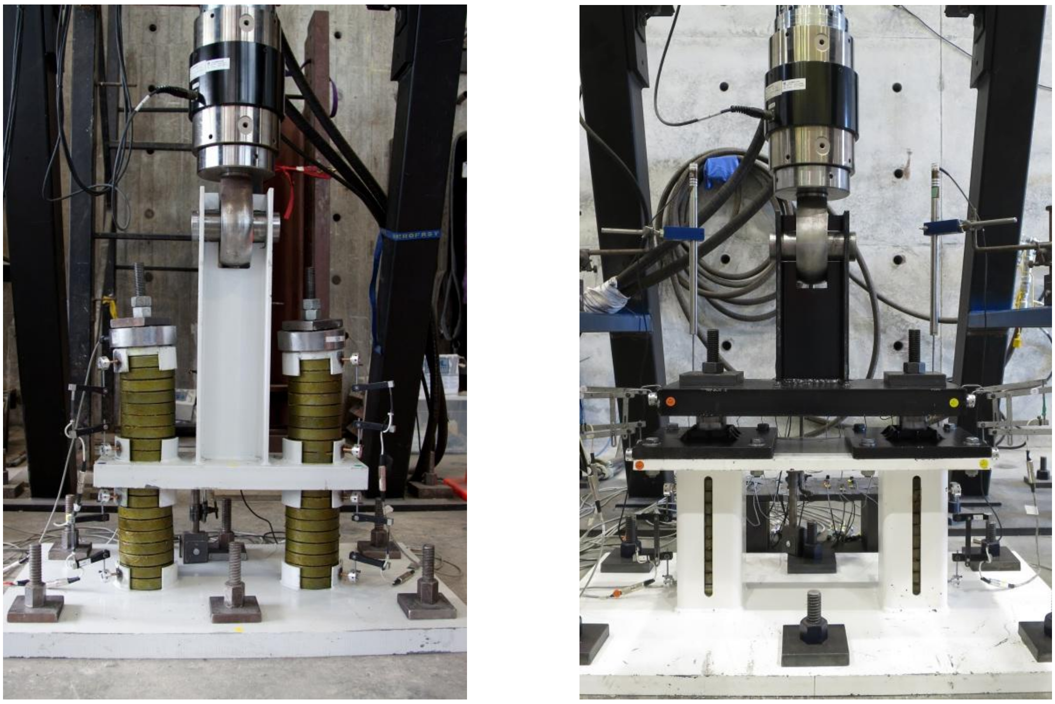
Figure 6: Test Result of Plain Class 8.8 M30 Threaded Rod with M24 Shank

a) **b)**

Figure 7: M30 Plain Class 8.8 Threaded Rod with M24 Shank
a) Yielded Threaded Rod; b) Yielding Region

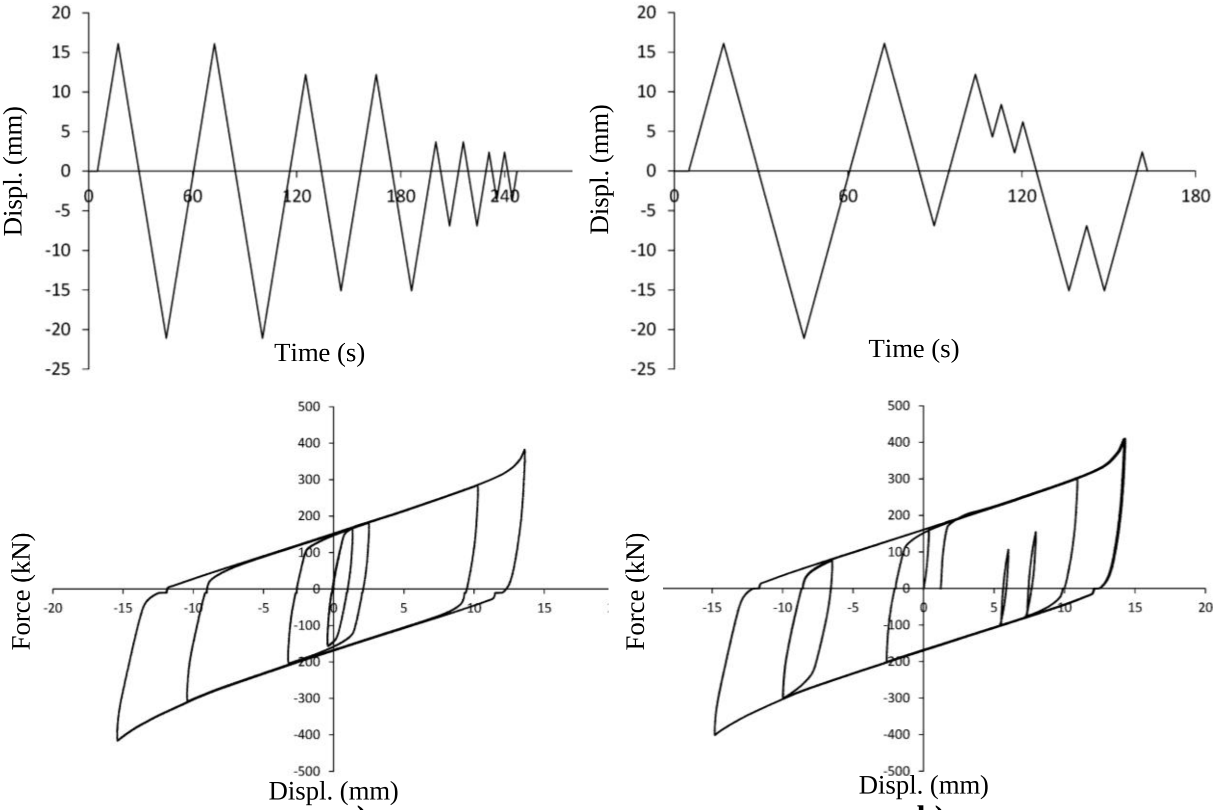
2. Double Acting Ring Spring Type I and Type II Testing

   Two unique designs of double acting ring spring systems have been developed and experimentally tested. The testing was conducted under low cyclic loading to observe the hysteresis curves, initial force to initiate elastic spring of the system, behaviour of the system after it is locked up, and the self-centring capability. Figure 8 shows double acting ring spring type I and type II test setup. The loading protocols and the test results of the double acting ring spring type I and double acting ring spring type II testing are shown in Figure 9 and Figure 10 respectively.



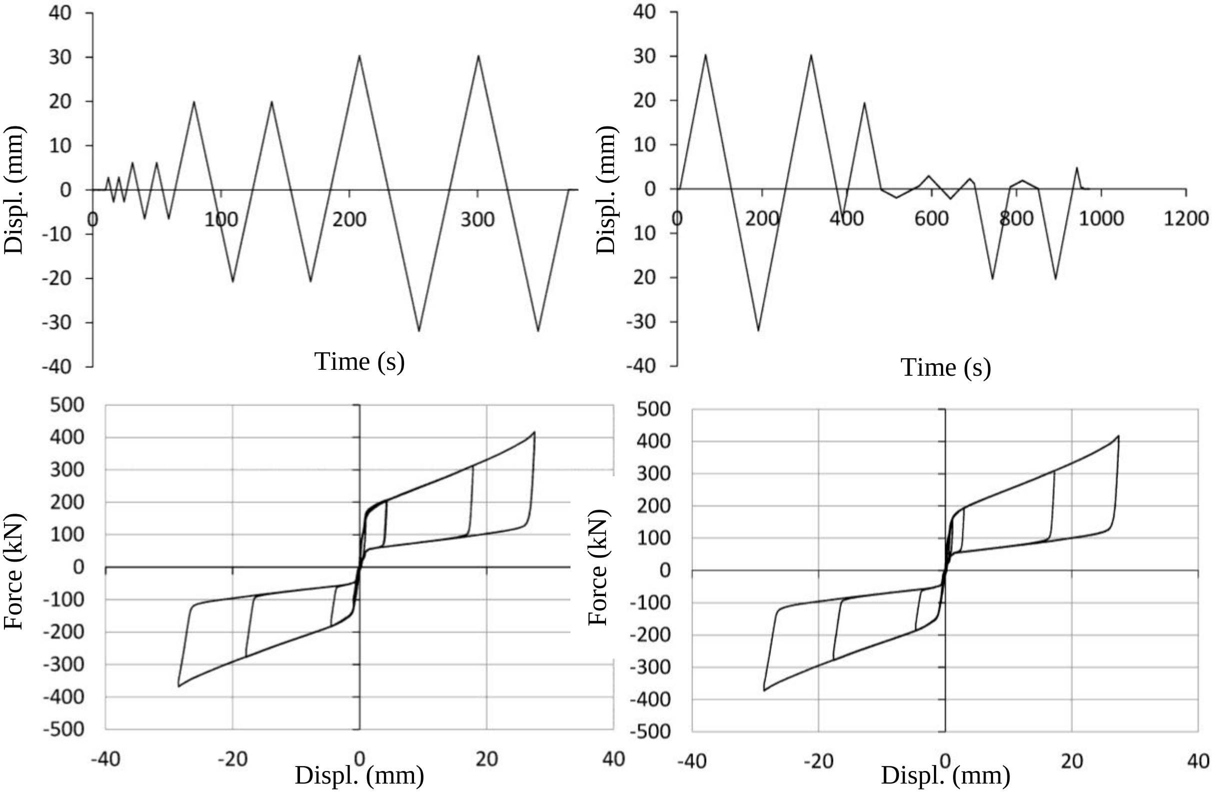
a) **b)**

Figure 8: Double Acting Ring Springs Test Setup
a) Type I; b) Type II



a) **b)**

Figure 9: Type I – Loading Protocols and Hysteresis Curves
a) Symmetrical Loading; b) Asymmetrical Loading



a) **b)**

Figure 10: Type II – Loading Protocols and Hysteresis Curves
a) Symmetrical Loading; b) Asymmetrical Loading

Type I and Type II systems showed stable and repeatable hysteresis loops at any loading rates as shown in Figure 9 and 10. In the Type I system, the magnitude of the diminishing oscillating force before it becomes too low to compress the spring determines the extent of actual self-centring of this system. Under diminishing action at the end of earthquake record, as will occur in practice, it comes close to fully self-centring. In the Type II system, the system dependably returns to its original position after unloading.

3. Bottom Storey CRCBF Testing (Rocking Frame)

   A two-thirds scale bottom storey CRCBF consists of 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 as shown in Figure 11. Two proposed types of joint connections for two frames have been fabricated. The first of these is where the beam and brace are passed through the concrete filled SHS column and simple fillet welded to the external face of the SHS to enable compression strut transfer to operate within the concrete core, as shown in Appendix 2. The second involves welding the brace to the collector beam joint then embedding both into the SHS column through a large window slot which is subsequently sealed with a cover plate, as shown in Appendix 3. Both are designed and detailed to achieve rigid connections between those components. By taking advantage of CRCBF symmetrical model, only a half part of the braced frame has been fabricated for these tests. Therefore, a vertical post has been provided to support the beam and to maintain the stability of the frame. The testing was conducted under slow-speed and high-speed cyclic testing and dynamic testing to observe the behaviour of the centralised rocking pivot, the double acting ring spring in a frame, and the beam/brace/column connections under cyclic loading which determines the behaviour of the rocking frame.

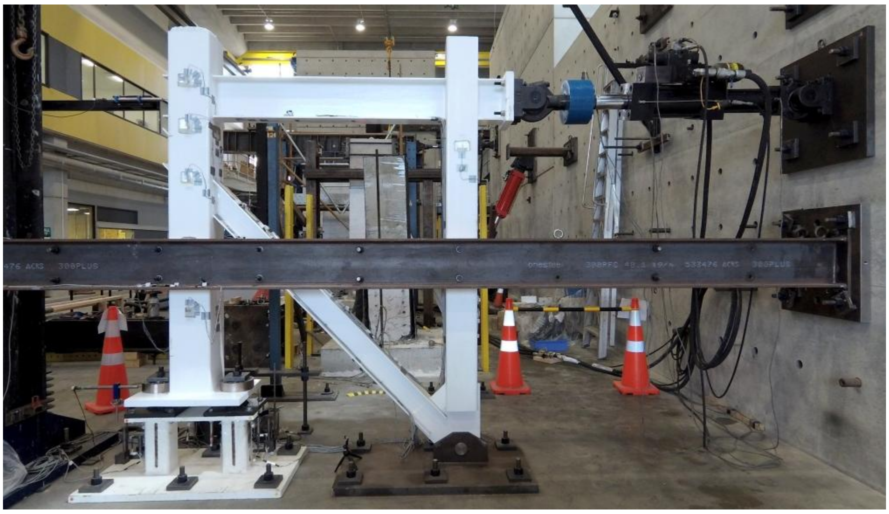
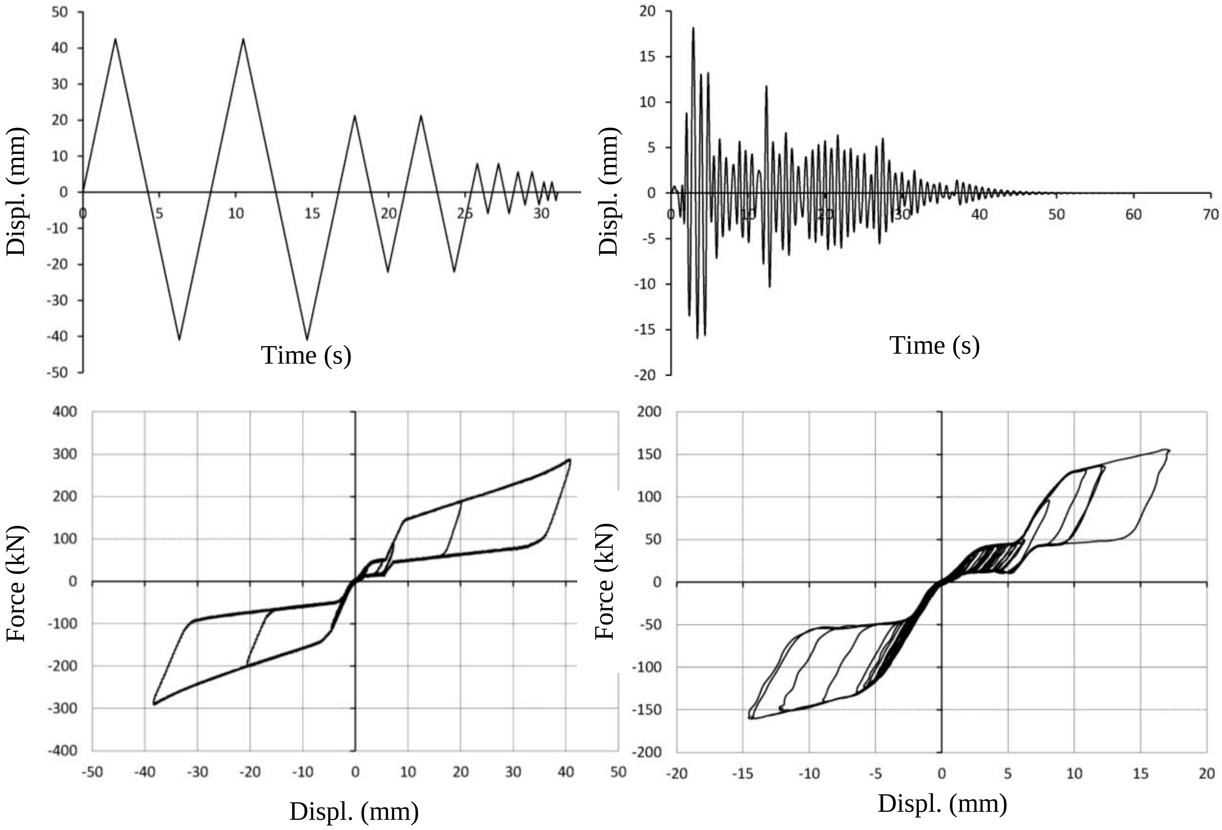


Figure 11: Bottom Storey CRCBF Test Setup

The loading protocols and the test results of the bottom storey CRCBF are shown in Figure 12.



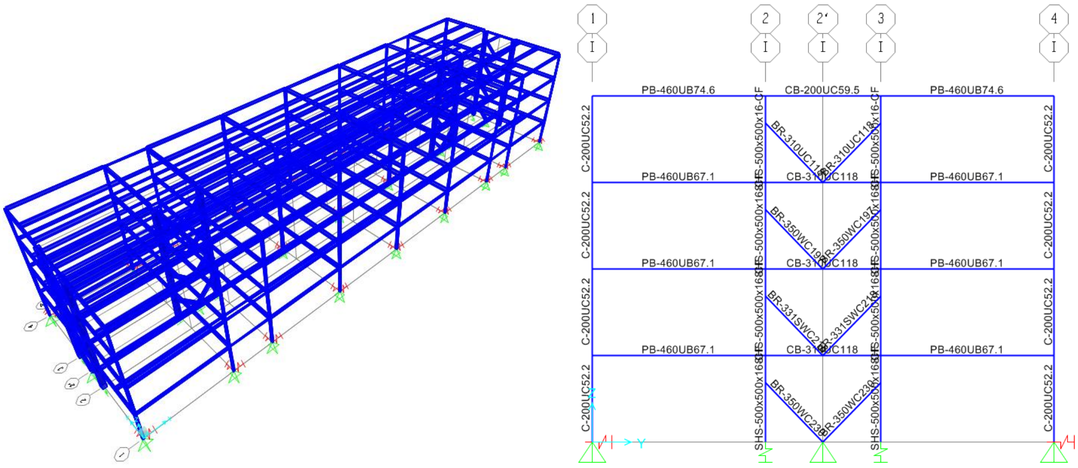
a) **b)**

Figure 12: Rocking Frame Testing – Loading Protocols and Hysteresis Curves a) Static Cyclic Loading; b) Dynamic Loading (El Centro 1940)

The experimental test results showed the behaviour of the double acting ring spring governed the global behaviour of the rocking CBFs showing stable and repeatable flag-shaped hysteresis loops under different loading rates and self-centring.

6. Prototype building in SAP2000

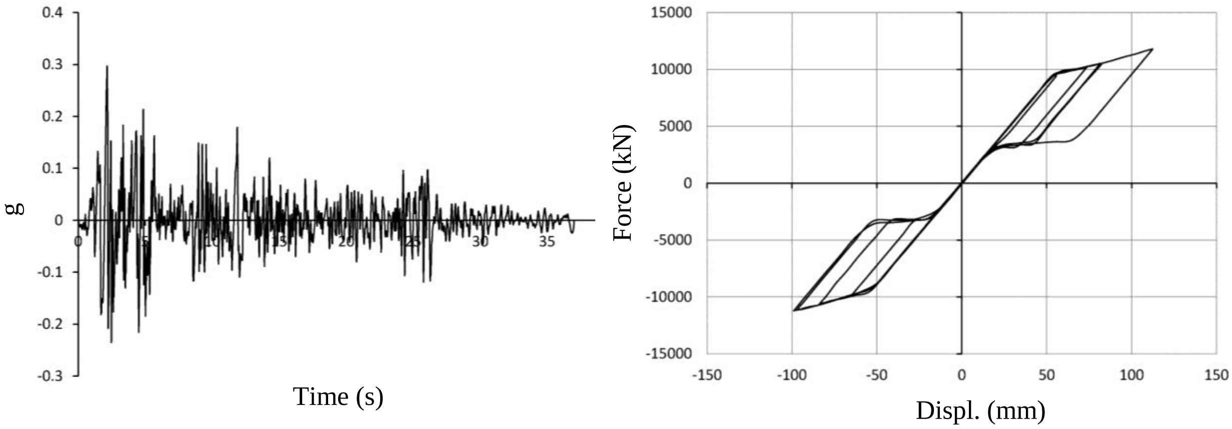
A four-storey building prototype has been used as an analysis case to develop the conceptual design and detailing requirements. The building utilising CRCBF system as the primary lateral resisting system is to be located in CBD of Christchurch with a deep or soft soil site (ClassD). The structural plan area is 71m by 21m as shown in Appendix 1 and the floor height for each storey is 3.75m. The building is planned for office space (live load 3.00kPa) and the roof is proposed as a green roof and an accessible roof (live load 4.00kPa). Superimposed dead load for the floor and the roof are 1.50kPa and 2.00kPa respectively. CRCBFs are placed at the perimeter frames and designed as one direction lateral resisting system. 3D model and CRCBF are shown in Figure 13.



a) **b)**

Figure 13: Prototype Building with CRCBFs
a) 3D Model; b) CRCBF

The earthquake record and the building behaviour are shown in Figure 14.



a) **b)**

Figure 14: Analysis Input and Output
a) El Centro 1940 Earthquake Record (PGA= 0.3G); b) Hysteresis Curves (PGA= 0.3G)

7. EQC Funding

EQC funding has been spent to purchase machined down threaded rods, double acting ring spring type II, 3 (three) bottom storey frames, and other important components to support those experimental testing.

8. Conclusions

Double acting ring spring type I and type II testing have been successfully tested under static and dynamic loading with stable and repeatable hysteresis loops. Those dissipate considerable energy and also self-centre after the cycles. SAP2000 hysteresis loops correspond to the rocking frame experimental test results. The experimental testing and SAP2000 analysis confirms the behaviour of double acting ring spring type II and rocking frame.

9. Acknowledgement

The author would like to acknowledge the support and guidance from AP Charles Clifton and Dr. Rick Henry and also the financial support from the University of Auckland through Doctoral Scholarship and PReSS account, QuakeCoRE extension scholarship, and New Zealand Earthquake Commission. The assistance from Ringfeder Power Transmission GMBH and UoA technicians is truly appreciated.

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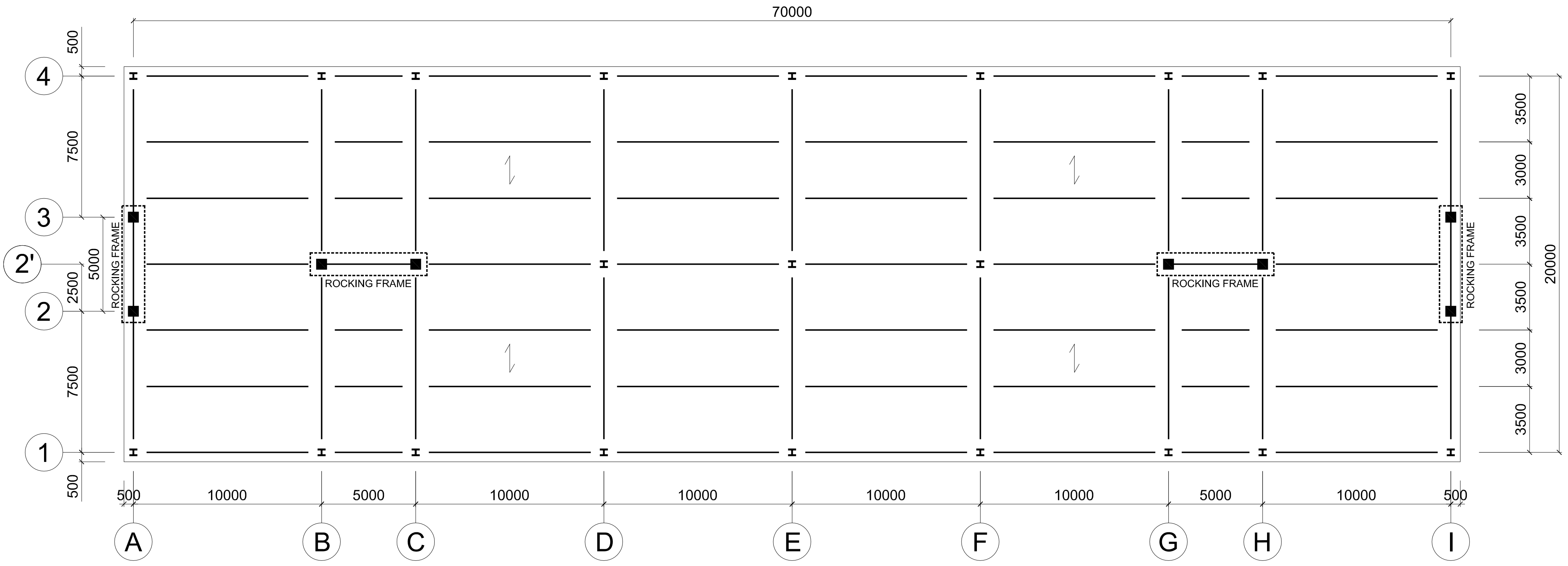
APPENDIX



FLOOR PLAN

NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETRES UNLESS OTHERWISE NOTED.
2. G300, Fy= 300 MPa IS USED UNLESS OTHERWISE NOTED.
3. DECKING: COMFLOR 60 DOUBLE SPAN WITH 0.75 DECK THICKNESS 0.75MM AND 130 MM SLAB THICKNESS.

PROJECT:
CENTRALISED ROCKING
CONCENTRICALLY BRACED FRAME
APPENDIX 1

DRAWING TITLE:
FLOOR PLAN

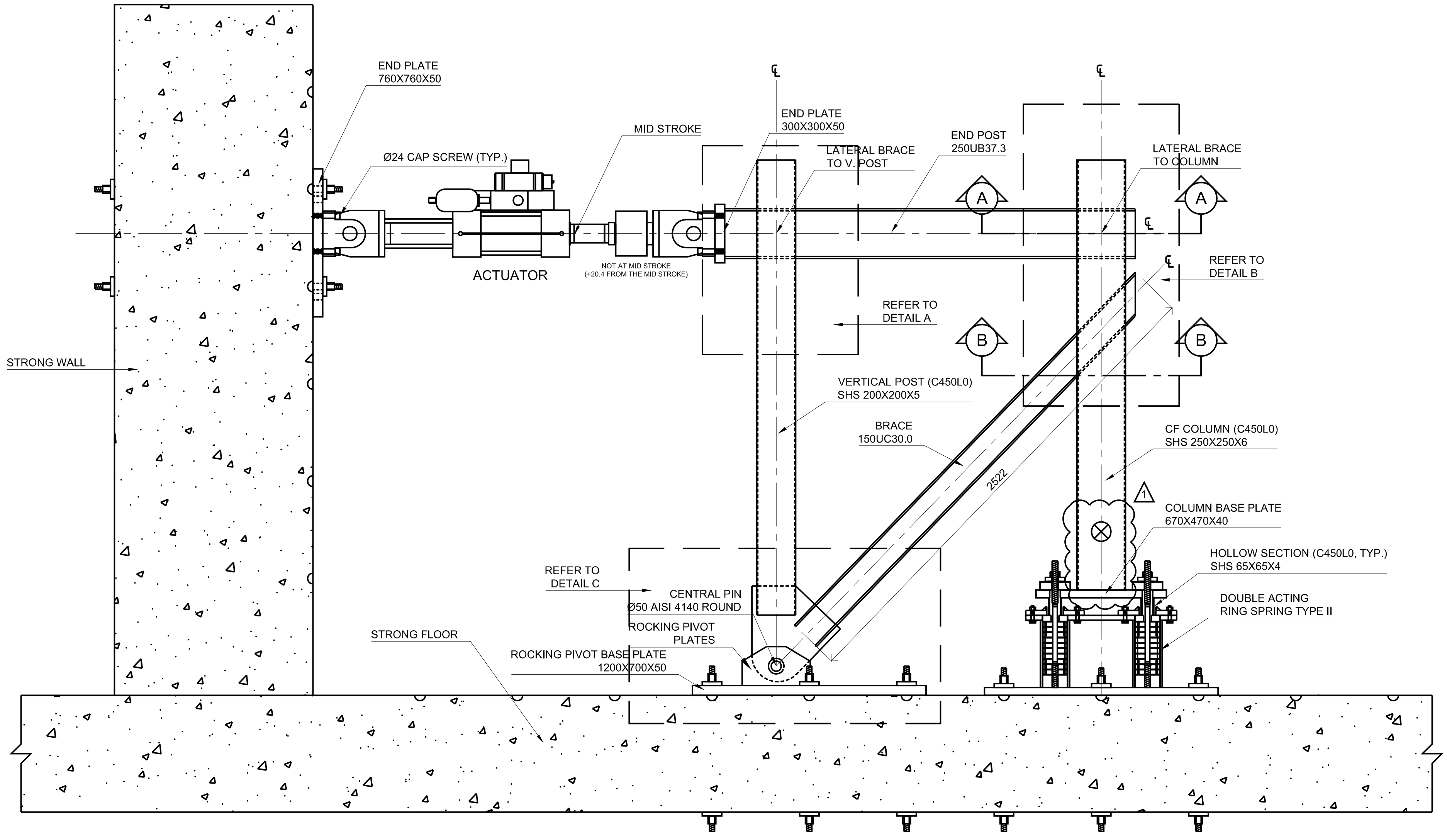
PROJECT NO: 1/2016
SCALE: 1:300
DESIGNED BY: GD
APPROVED BY: CC
ISSUED FOR: EQC FINAL REPORT

NO.	DATE	DETAILS

REVISION: 0
DATE: 18/03/16

DRAWING NO:
1/1

NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETRES UNLESS OTHERWISE NOTED.
2. ACTUATOR FORCE CAPACITY IS 330 kN (±150mm).
3. G300, fy= 300 MPa IS USED UNLESS OTHERWISE NOTED.
4. CONCRETE fc'= 50 MPa WITH CONTROL 40 IS USED TO FILL THE COLUMN.
5. CF IS CONCRETE FILLED, REC IS RECTANGLE.



BOTTOM STOREY FRAME TESTING (JOINT TYPE I) - OVERVIEW

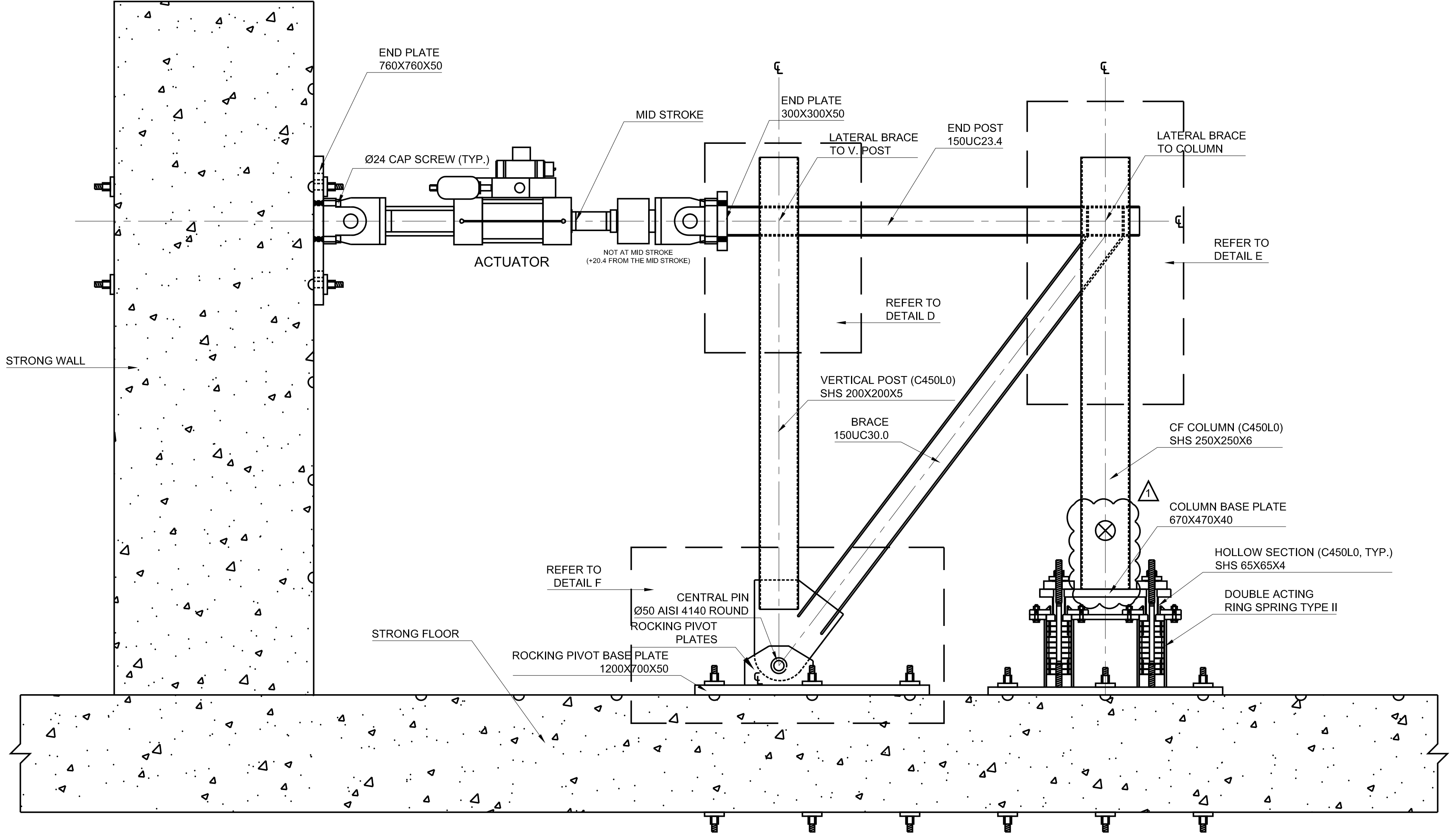
DRAWING TITLE:
BOTTOM STOREY CRCBF TYPE I
APPENDIX 2

PROJECT NO:
SCALE: 1:30
APPROVED BY:
DATE:
ISSUED FOR: EQC FINAL REPORT

DESIGNED BY:
GARY DJOJO (ID: 1756539)
E-MAIL: gdjo001@aucklanduni.ac.nz
THE UNIVERSITY OF AUCKLAND
FACULTY OF ENGINEERING

DRAWING NO: 1/1
DATE: 22/11/15
REVISION: 1

NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETRES UNLESS OTHERWISE NOTED.
2. ACTUATOR FORCE CAPACITY IS 330 kN (±150mm).
3. G300, fy= 300 MPa IS USED UNLESS OTHERWISE NOTED.
4. CONCRETE fc'= 50 MPa WITH CONTROL 40 IS USED TO FILL THE COLUMN.
5. SWEEP BLAST IS APPLIED TO ALL COMPONENTS
6. WHITE OVERCOATING PAINT IS APPLIED TO BEAM, BRACE, COLUMN, COLUMN BASE PLATE, AND VERTICAL POST.
7. CF IS CONCRETE FILLED, REC IS RECTANGLE.



BOTTOM STOREY FRAME TESTING (JOINT TYPE II) - OVERVIEW

DRAWING TITLE: BOTTOM STOREY CRCBF TYPE II APPENDIX 3	PROJECT NO:	SCALE: 1:30	DESIGNED BY:	GARY DJOJO (ID: 1756539) E-MAIL: gdjo001@aucklanduni.ac.nz THE UNIVERSITY OF AUCKLAND FACULTY OF ENGINEERING	DRAWING NO: 1/1	DATE: 22/11/15	REVISION: 1
	APPROVED BY:	DATE:					
	ISSUED FOR: EQC FINAL REPORT						