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A PRACTIONERS GUIDE TO DESIGN AND DELIVERY OF CONTROLLED ROCKING STEEL BRACED FRAME STRUCTURES

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ABSTRACT

Ductile steel frame systems such as eccentrically braced frames whilst reliable, cost effective and widely utilized all require significant post event repair, replacement or even demolition. In 2005 the steel industry identified a gap existed for a resilient and stiff steel braced frame that could demonstrate reliable energy dissipation, self-centering and nominal floor slab or secondary structural element damage. The system had to be easily repairable, simple to design and detail and concentrate the inelastic energy into reliable and replaceable parts and components. Thanks to the extensive and pioneering work in displacement based design by ***Priestley et al***, research within New Zealand Universities over the past ten years into rocking response of structural steel frames has progressed significantly generating over fifteen years of extensive tertiary level research, the cyclic nature of seismic demands, coupled with control mechanisms, engineers are able to manipulate building element response during seismically induced rocking.

A rocking bracing structural element can be formed in steel, concrete and timber. In essence once the hold down resistance, gravity and any bearing/restoring forces are exceeded during extreme events the tension fibre is prone to lifting off. Without adequate tension control, increasing force resistance, or other re-centering forces without lateral force reversal, rocking structures need could ultimately experience rigid body overturning.

Controlled Rocking Steel Braced Frames (CRSBF's) are a special form of structural system that allows small vertical displacements, which when controlled with post tensioning or springs combined with energy dissipation devices, can reduce foundation hold down forces and form part of a low damage or recoverable structural system. The CRSBF system focuses energy dissipation into replaceable connections and/or components which require the primary structural elements to be designed to remain elastic. The elastic CRSBF must be well connected to gravity systems and diaphragms via robust steel detailing which are needed to ensure principles of the steel code are adhered to. The selection and use of rocking structural systems requires specialist knowledge of their behaviour, key parameters and the application of suitable analysis and design techniques to deliver the intended performance.

Steel Construction New Zealand (SCNZ) have conceived and facilitated the development of a guideline to aide designers in their consideration and use of CRSBFs. The guideline highlights key equations, parameters, considerations and provides background knowledge to designers considering CRSBF applications.

This paper provides the authors views and experience following involvement in the design and detailing of several building projects harnessing CRSBFs as a primary lateral seismic force resisting system. The paper identifies key concepts, a proposed design process, analysis, and detailing. The paper also provides an introduction on how a designer may harness the benefits of Steel Construction New Zealand's new guideline for Controlled Rocking Structures. This paper does not duplicate these formulae or parameters here but provides high level guidance only. In addition to the guideline a comprehensive reference library of papers is intended to be made accessible via the SCNZ website.

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1.0 Introduction

In 2015, building developers expect structural engineers to present the latest research and developments in their design options, whilst complying with all current design standards. In New Zealand, a structural solution is always expected to be economic. This expectation can limit consideration of low damage design due to the cost of implementing available technology.

Modern structures are more rigorously designed, and in the more seismically active areas of New Zealand, to higher levels of lateral acceleration than were previously required by previous historic versions of loading standards. However compliance with strength and displacement requirements of our standards may not necessarily address or limit control of ‘damage’. Modern designers consider and choose appropriate levels of ductility for their designs, but this approach inevitability results in high damage in primary structural members such as columns, beam/column joints of moment frames and active links within eccentrically braced frames.

These high ductility systems when well detailed are undoubtedly capable of surviving a big event and dissipate seismic energy via damage predetermined structural hinge zones. Although this damage may not lead to system instability or failure, the resulting structural damage from significant earthquakes will require significant repair or as seen in Christchurch after the 2011 earthquake leave properties untenable and requiring demolition. Damaged elements within such frames will require significant repair, replacement. Demolition.

It has been a well-documented trend over the last ten years for leading researchers at University of Canterbury (UoC) and University of Auckland (UoA) to consider and explore the various benefits a ‘low damage design’ philosophy and structural design process, and its application to numerous forms of technology. This trend and subsequent application post event has helped expand the New Zealand’s engineering knowledge and grow our property industry. In the USA, concurrent researchers and industry practioners have joined forces to establish the Resilience Council, and have created guidelines for Resilience such as REDi a resilience rating system as well as developing various tools for assessing the relative performance of structural systems in achieving resiliency objectives.

Following Christchurch events, perception and expectations have now changed with New Zealand’s property clients recognizing actual building performance will always result in the need to plan post event recovery following large seismic events. Consideration of new low damage systems have resulted in some owners seeking levels of resilience beyond code through the application of new seismic technologies.

New Zealand building owners have learnt from the Canterbury experience, and now understand that even code compliant ‘modern’ buildings may not equate to being useable following a large seismic event. It’s likely that even modern buildings will require façade repair, ceilings and fitout repair and potential primary structural repairs. The industry has learnt that structural damage needs to be planned for in design, controlled and limited, to ensure a building can remain useable after a large earthquake.

While numerous technologies have been explored to reduce building damage and solutions have been presented to consulting engineers, a prevalent market perception is still that these solutions are neither elegant nor cost effective to implement. The building industry perceives low damage means all of building resilience which is not correct with significant multi-disciplinary effort. A low damage structure is not a resilient building, and engineers need to improve communication with their clients.

A gap exists between what structural engineers call low damage design and what clients understand and perceive this to mean. Engineers understand that low damage systems simply mean a “recoverable structural system”, hopefully with low drifts and damage located in easily replaceable and repairable parts and components. To date only a small number of steel structures in New Zealand have been designed and detailed to achieve a low structural damage philosophy. These modern structures present a halfway house between resilient buildings (seismically isolated) and code compliant buildings that only consider life safety at Ultimate limit state (ULS) event levels of seismicity.

To provide low damage recoverable structural systems using steel framed construction, the solution structural engineers are seeking is a simple semi-rigid beam column jointing system that is cost effective to fabricate and install, ensures stability, controls hinging, limits building drifts and most importantly limits primary structural damage. These systems would ideally also control and limit forces on other primary structural elements and supporting foundations, be self-centering and have minimal post event residual displacements.

Controlled Rocking steel braced frames (CRSBF’s) is the steel industries solution for this need.

Leadership by SCNZ has enabled practicing engineers, researchers and experts to collaborate and develop a solution for controlling seismic damage in steel framed buildings. The technology is now economic and viable and if detailed will achieve the recoverable structure objectives of low damage.

The Controlled Rocking Steel Braced Frame (CRSBF's) Design Guideline is a Steel Construction New Zealand (SCNZ) and industry sponsored document, created to enable experienced structural engineers to consider and harness the potential benefits of this type of this alternative structural system. The guideline was developed to enable the practicing structural engineer's access CRSBFs, relevant and current research, and design considerations for the use of the technology. The guideline provides designers with general guidance on its application, limitations and key considerations.

This paper does not duplicate key formulae or parameters herein but provides high level guidance only. In addition to the guideline a comprehensive reference library of papers which will be accessible via the SCNZ website. The guideline provides two worked preliminary design examples, relating to a load bearing and a non-load bearing CRSBFs. The design examples will aid designers in their preliminary design to achieve frame sizes and consider the appropriate design affects.

2.0 CRSBF Concepts

This section summarizes key concepts of the CRSBF guideline, important design considerations including; establishing a client understanding of seismic performance brief criteria, determining when to use CRSBF's, CRSBF behaviour, key performance considerations and damage performance of CRSBFs. More detail and reference material can be found in Design Guideline for Rocking Steel Braced Frames, SCNZ' report 110; 2015.

Client brief -Establishing seismic performance criteria
Critical to the development of any building concept design is to establish performance expectations with the building owner/occupants. These key parameters outline how a code compliant building is intended to perform during serviceability and ultimate limit state seismic response. Designers can either adopt a code minimum compliant approach or set other levels of resilience beyond code that relate to a specific owner's operational continuity expectations.

This data should be located within the design philosophy section of the structural engineer's features report, for every building design. This table should clearly convey conceptual information in relation to performance to aide building owner and/or tenants develop a deeper understanding of the benefits of each structural concept. As an example Table 1 below identifies expected seismic performance of a normal, non-rocking building during various return period seismic events. In comparison, Table 2 below outlines criteria that may be considered for a code compliant CRSBF building, that ***does not*** have any specific low damage objectives. The table outlines the intent of the CRSBF behavior in response to different levels of seismicity.
If specific low damage design objectives are required it's important to express whether these are achievable with each concept – for instance without reducing floor acceleration inputs via damping and/or isolation, it's unlikely a reduction in floor accelerations and resulting ceiling/fitout damage will be achieved.

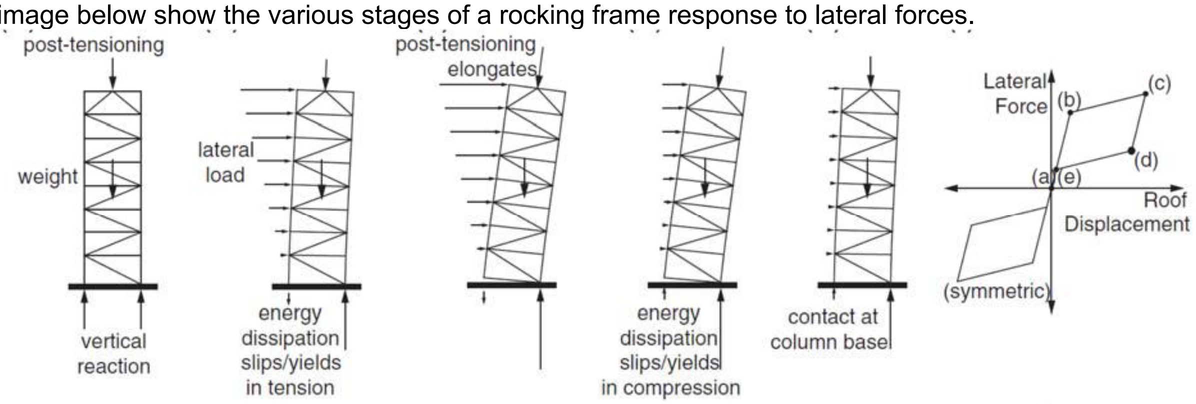
Limit State Criteria – Minimum Code Compliant – Normal Buildings					
Limit State (Earthquake considered)	**Importance Level**	**Return Period (events per interval)**	**Building - Probable Post Event State**	**Post Event – Use Requirement**	**Expected Loss State**
Serviceability Limit State (SLS)	2	1 in 50	Minor nonstructural but no compromise to function allowed	Fully - Operable	Minor
Ultimate Limit State (ULS)	2	1 in 500	Building may be heavily damaged but must allow safe egress	Non Operable – heavily damaged – may need to be demolished	Major
Maximum Considered Event (MCE)	2	1 in 2,500	Intent of the code and materials standards is that at MCE levels building shall not collapse	Non Operable – heavily damaged – may need to be demolished	Total

Table 1 – Limit State – Seismic Performance and post event use – Normal Buildings

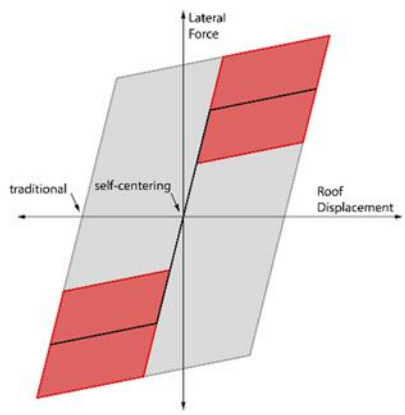
Limit State Criteria – Minimum Code Compliant – Controlled Rocking Steel Braced Frames						
Limit State (Earthquake considered)	**Importance Level (IL)**	**Return Period (Events per interval)**	**CRSBF Column Behavior (Rocking State)**	**Building - Probable Post Event State**	**Post Event – Use Requirement**	**Expected Loss State**
Serviceability Limit State (SLS)	2	1 in 50	Static(unresponsive	Minor nonstructural damage only but no compromise to function allowed	Fully - Operable	Minor
Ultimate Limit State (ULS)	2	1 in 500	Gravity and uplift resistance systems overcome, damper engaged and column small uplift occurring in response to cyclic loading) – rocking occurring	Safe egress ensured during/following event. Primary structure largely undamaged CRSBF uplift fuse may have undergone inelastic strain. Building contents façade and services may be damaged	Non Operable – damaged fitout due to floor level shaking – high levels of repair or worst case demolished	Considerable
Maximum Considered Event (MCE)	2	1 in 2,500	Gravity and uplift resistance systems overcome, damper engaged and maximum column uplift occurring in response to cyclic loading) – rocking occurring	Intent of the code and materials standards is that at MCE levels building shall not collapse Primary structural hinges have occurred and requiring fuse replacement (yielding bolt and UFP replacement. Fitout and non-structural component replacements	Non-operable – heavily damaged – may need to be demolished	Major

Table 2 – Limit State – Seismic Performance and post event use – Controlled Rocking Steel framed Buildings

Rocking Frame Behaviour – Key Differences from other systems
The image below show the various stages of a rocking frame response to lateral forces.



The above images represent a simplified response of post tensioned controlled rocking steel braced frames
a). Braced frame at rest
b). Onset of rocking after overcoming initial gravity and friction resistance of energy dissipation
c). Response a maximum displacement with rocking base gap at maximum
d). Response during self-centering with open gap closing, again overcoming friction resistance of energy dissipation in reverse
e).Gap full closed upon onset pf cyclic loading reversal.
f). Resulting flag shaped hysteresis of rocking system behaviour.
When compared with traditional systems, the red colored self-centering pinched hysteresis sees restoration back through the central axis with limited losses. In the adjacent image the grey area reflects energy losses comparable non-rocking systems experience.



Considerations for rocking structures (CRSBFs) – General

A controlled rocking steel braced frame (CRSBF), relies upon on a stiff, concentrically braced steel frame (or similar rigid body) that is connected to its foundations via a tension limited hinge mechanism. CRSBF's provide initial resistance to uplift through gravity, friction and/or sliding resistance and then via yielding of U-Shaped flexural plates. Once gravity and initial resistance features are overcome the CRSBF and its base connection allows its column to experience vertical uplift between baseplates and the supporting foundations. The uplift movement is controlled via a pre-tensioned steel damper or elongation of post tensioning. Building drifts and displacements should be similar or less than traditional structures. Floor accelerations and higher mode affects and contributions can be higher in rocking structures.

CRSBFs are best suitable within regular buildings, concentrically loaded frame locations, where the frames are either exposed or easily accessible for post event repair. The frames will prove most reliable when located on the transfer or short side of rectangular shaped buildings. The frames can be either load bearing or non-load bearing, but must be provided adequate out of plane stability during seismic response. The frames need to be designed as low ductility or elastic and force the inelastic demands into the UFP's the dampers and sliding connections. Reliable and elastic floor diaphragm connections are essential for ensuring floor shear forces are evenly distributed to the vertical frames. The floor to frame connections must be detailed to enable and accommodate the vertical and lateral movement induced by the CRSBFs. The frames are best enclosed from weather to ensure durability of the dampers, PT and any friction connections which are less reliable if exposed to moisture and rust.

CRSBFs may be less suitable for irregular buildings and complex structures, which have multiple load paths and out of plane loading conditions. For taller structures multiple rocking mechanism (i.e. at two or more floor levels), and the introduction of nonlinear diagonal brace elements may be required to reduce accelerations and higher mode affects.

Table 3 below outlines response of performance criteria that is recommended for the design of CRSBFs.

Element Response vs limit state demand	**SLS Earthquake**	**ULS Earthquake**	**MCE Earthquake**	**ULS Wind**
Uplift (column decompression)	Load-Bearing: N Non-Load-Bearing: Y	Y	Y	N
Displacement limits	As per NZS 1170.5 Clauses 7.4-7.5	As per NZS 1170.5 Clauses 7.4-7.5	Not checked	As per AS/NZS 1170.0 Appendix C
Overturning	N	N	N	N
Yielding of post-tensioning	N	N	Y	N
Failure of post-tensioning	N	N	N	N
Deterioration of energy dissipation elements	N	Y	Y	N
Residual displacements	As per code requirements for new construction	No requirements but recommend less than 0.2% residual drift to remain functional	No requirements	As per code requirements for new construction
Floor accelerations	No requirements	No requirements	No requirements	No requirements
Failure of diaphragms, collectors, or connections	N	N	N	N

Element Response vs limit state demand	SLS Earthquake	ULS Earthquake	MCE Earthquake	ULS Wind
Sliding along rocking joints	N	N	N	N
Inelastic response of frame members	N	N	N, although not a requirement would represent best practice and understanding that the ductility shall be located in replaceable parts and components not the primary structure	N

Table 3 – Seismicity and potential post event operation targets – Controlled Rocking Steel framed Buildings

Considerations for using CRSBFs

a). Building height

One of the principle advantages of CRSBFs is that a braced frame can be used without requiring the frame members to behave inelastically. Therefore, the elastic stiffness of a braced frame can be achieved without the need to follow code clauses that discourage tall concentrically braced frames, including both height and member compactness limits. Some of the greatest benefits of CRSBFs relative to other systems are for taller structures. Although SCNZ report 110 does not specify any height restrictions for CRSBFs, the relative importance of higher mode effects increases with height, making taller CRSBFs less economical unless higher mode mitigation is considered and implemented.

b). Braced Frame Configurations - load-bearing and non-load-bearing options

The SCNZ guideline distinguishes between CRSBFs that carry their tributary gravity loads and those separated from the gravity framing system.

- Load bearing CRSBFs - connected to floor systems with gravity load bearing columns
- Isolated from gravity CRSBFs - disconnected to floor systems with gravity load bearing columns
- Table 4 below compares the relative considerations for these two approaches.

Load-Bearing	Non-Load Bearing
Gravity loads are used to help resist overturning moments associated with lateral seismic forces.	Gravity loads must be carried by a separate gravity framing system, resulting in additional structural columns, complicating architectural and façade detailing considerations
Conventional detailing is likely to be suitable for floor-frame connections.	Specialised detailing is required to transfer seismic forces without allowing floors to uplift with the controlled rocking frame.
Frame uplift is expected or may damage floor systems. Careful detailing with plates may reduce this issue	Frame uplift is not expected to damage floor systems.
Flooring system may restrain uplift.	Floor-frame connections are designed to ensure that flooring systems do not restrain uplift.
Column forces may be amplified by compression impact with the foundation if gravity load is large.	Peak column forces are likely to occur at the peak system deformation, rather than immediately after impact, so impact is unlikely to influence peak column forces.
Horizontal floor acceleration spikes may occur after column impact on the foundation	Horizontal floor acceleration spikes following impact are unlikely

Table 4 - Comparison of load-bearing and non-load-bearing CRSBF options

c). Singular or Coupled CRSBF's

Within the above there are two further sub categories as outlined in the below image;

- Single CRSBFs
- Coupled CRSBF's – connected via floor level moment resisting coupling beams(as used by Aurecon at Te Puni Student Village) or shear fuse links(as researched by Deirelein et al)

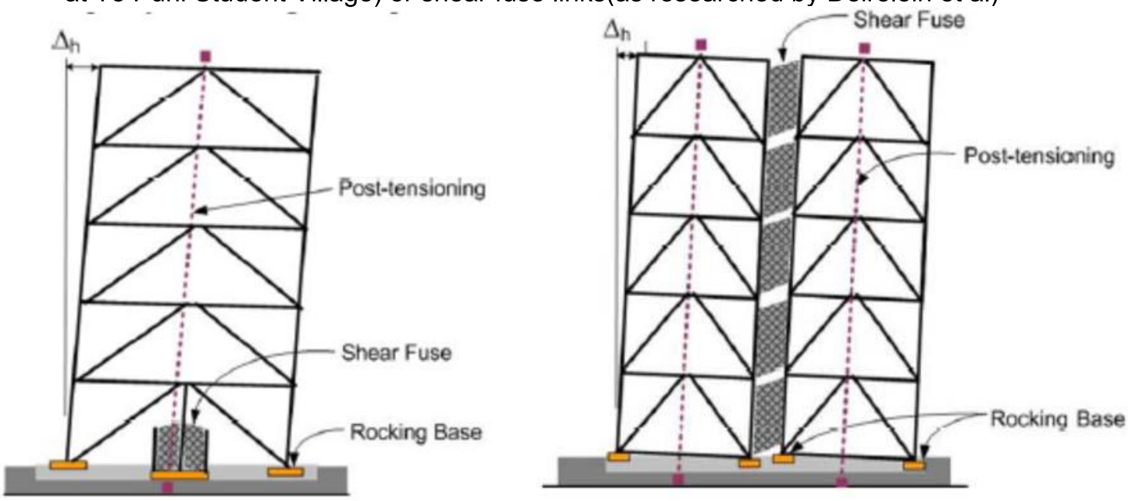


Figure 2 *- Single and coupled rocking braced frames -* (source G. Deirelein, Stanford)

d). Other Concepts

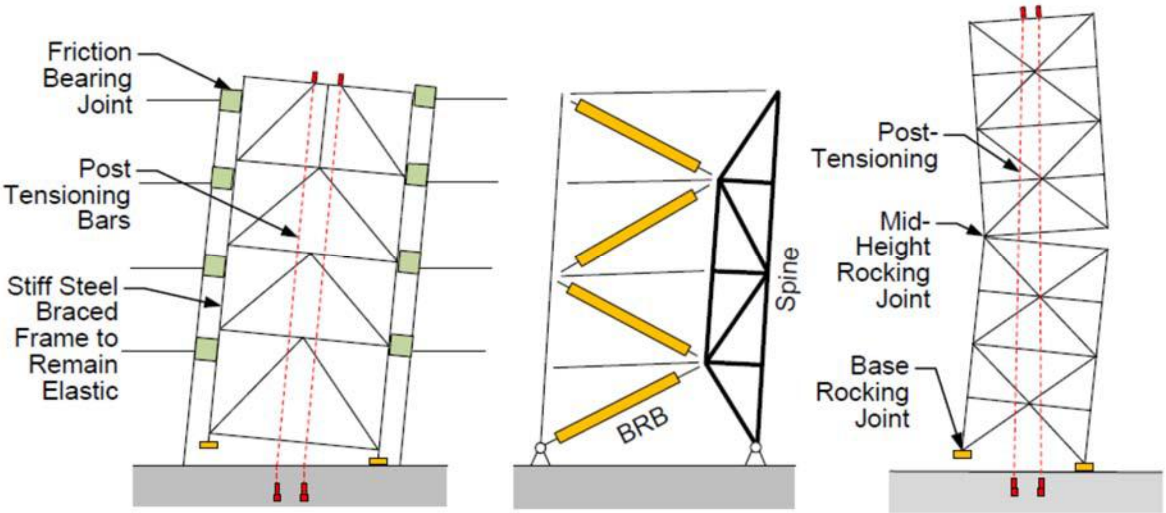


Figure 3 *- Single and coupled rocking braced frames -* (source Eatherton et al, 2012)

Expected structural damage when using controlled rocking frames (CRSBFs)

Controlled rocking steel braced frames are considered to be a relatively high-performance system because the amount of structural damage is expected to be reduced relative to conventional systems. It is expected that a building that uses CRSBFs could more rapidly returned to occupancy after a design-level event because primary structural elements should be undamaged. Despite the good structural performance of CRSBFs, non-structural damage is still expected to be similar to conventional structural ductile systems. In particular, peak Storey drifts with CRSBF system will be similar to conventional structures. These deformations are estimated as part of the design process, and they can be reduced by controlling and increasing the elastic stiffness of the bracing system.

The peak horizontal floor accelerations are also not expected to be reduced relative to conventional systems, and they may even be larger for rocking systems that carry significant gravity loads. However, based on the observed response of non-structural elements in a range of flexible and stiff multi-storey buildings in the 2010/2011 Christchurch earthquake series, stiffer buildings deliver lower non-structural damage and less disruption than flexible buildings. Care is required in detailing floor to frame connections as proposed by Sause in 2009 and reiterated by MacRae et al in 2013.

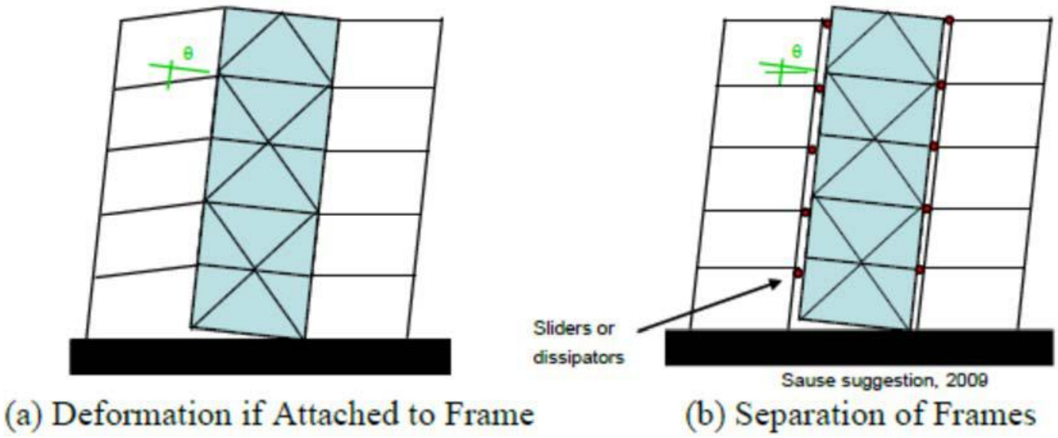


Figure 4 *– Rotation generated damage at connections of a CRSBF* - (source MacRae et al, 2013)

Comparison of CRSBFs performance with other structural system configurations)

At MCE codes and standards require collapse prevention but owners may desire or expect that their buildings may be repairable. Clarification of performance at or following these extreme events is required to provide clarity to owners and users of large buildings in high seismic environments. Resilient Buildings (such as seismically isolation) routinely consider MCE event and this should be considered relevant if low damage is a client's objective.

In the consideration of the relative performance of alternative structural systems engineers need to understand the relative behavioural characteristics of building types. To achieve these the industry needs to develop building typology and fragility data for application with assessment tools such as FEMA56. This tool (when appropriately configured) enables designers assess the relative performance and relative cost/benefits of each structural system. Benefits will vary for each building configuration and arrangement.

Obtaining building consent – alternative design process

The intent of the SCNZ design guide is to be consistent with current New Zealand seismic design standards, it is not intended as a normative supplement to the provisions of NZS 1170.5 or NZS 3404.

CRSBF structures are considered an alternative solution according to Clause 1.5 of NZS 3404 and are likely to require more review than conventional systems in order to obtain building consent. The author recommends making contact with SCNZ, senior staff at UoC or UoA or with the author to identify appropriate and experienced structural engineers who can provide peer review (PS2) services to aid the design process.

Early engagement with the peer review team is essential to ensure fundamental principles progress in line with current research and development.

3.0 CRSBF's - Design Process

The below flow chart outlines the preliminary design process for the design of CRSBF structures (ref SCNZ report 110; 2015)

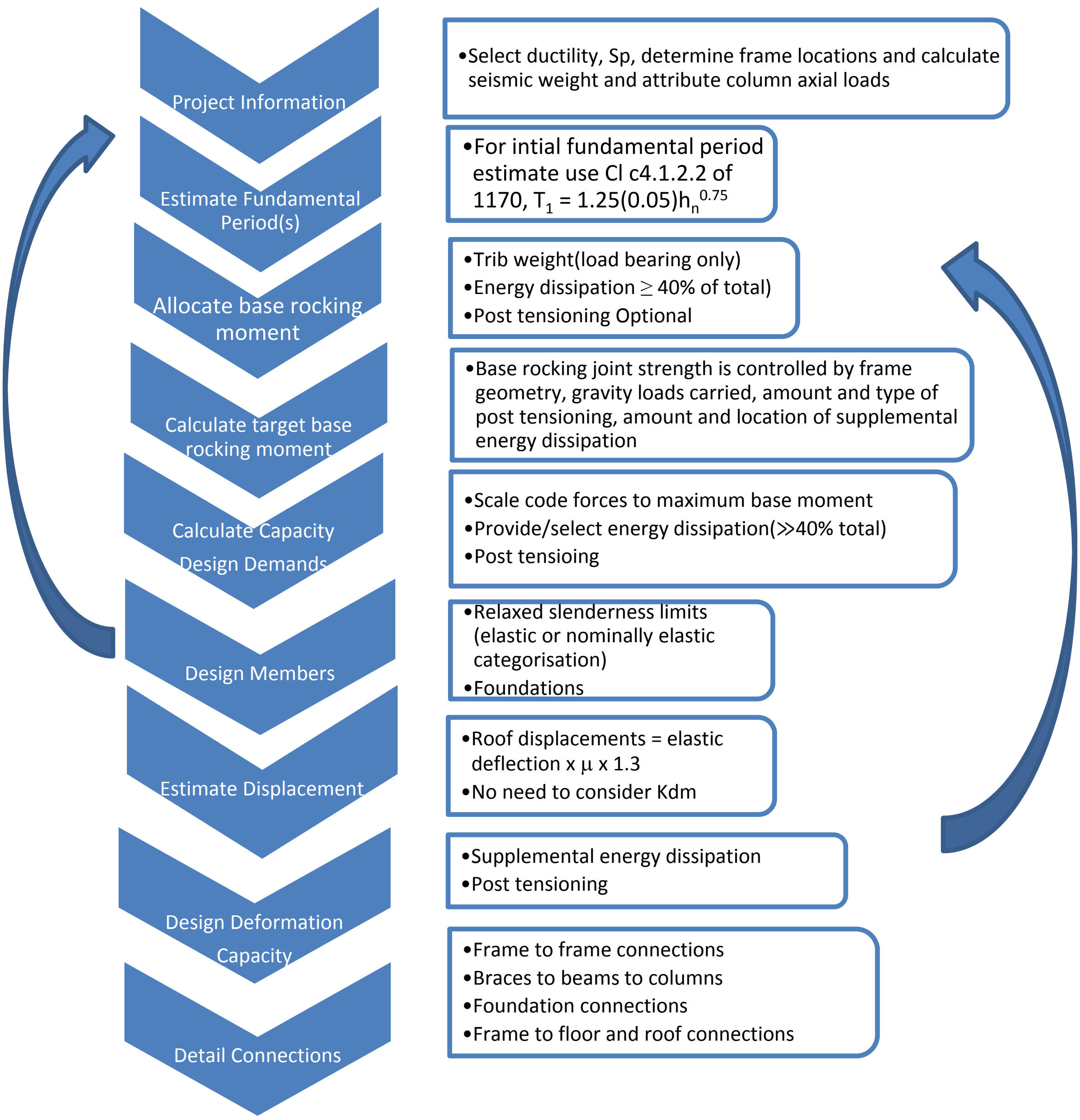


Figure 4 – Controlled Rocking Steel Braced Frames – Design Process

The above figure shows an overview of the methodology that is followed by SCNZ report 110; 2015 guide. The methodology can be summarized into three key procedural steps;

Step 1 – Determine and Allocate Rocking Base Moments

First, displacement-related limit states are addressed by ensuring that the rocking moment is large enough and by providing/adding sufficient supplemental energy dissipation. This initial step involves determining whether or not the frame will be detailed to carry significant gravity load, determining appropriate ductility factor, calculating the reduced base overturning moment, and selecting the form of energy dissipation (springs or post-tensioning). Research suggests it's important to provide at least 40% of the base rocking moment as rigid body rocking alone does not generate significant energy dissipation.

Step 2 – Calculate force demands on components
The second step of the methodology addresses acceleration-related (force-related) limit states through capacity design. The guideline outlines methods for estimating the peak force demands on members of the frame, as well as calculating the base shear that must be transferred through the foundation into the ground.

Step 3 – Detail key connections
The third and final step of the methodology is to detail the key connections to withstand the forces and deformations that were calculated in the previous steps. It is recommended that the consultant structural engineers satisfy themselves (and their peer reviewers) of developing suitable robustness and alternative load paths of all key connections. The designer should consider the requirements NZS3404 in terms of capacity design, hierarchy and detailing, however there are several departures in terms of member classification and slenderness limits. We recommend the reader review the SCNZ CRSBF Design Guideline report 110; 2015 for more detail on the proposed design process. Rather than duplicate the formulas and parameters outlined in the above guideline, please refer to section 4 and 5 of the guideline.

In addition L. Wiebe PhD thesis "Design of Controlled Rocking Steel Frames to limit higher mode effects" – referenced as 18 therein) is particularly useful for providing more background to the proposed design process.

4.0 - Analysis Considerations

Force vs displacement based approaches
Rocking systems are governed and controlled by the force/moment required to achieve rocking (base rocking joint) and then once activated, by the stiffness of the structure rocking modes of response. Much has been written on this subject and the references within SCNZ's report 110; 2015 provide excellent background. In summary both force based and displacement based approaches maybe utilized. The author has experience in conducting displacement focused, force based design approach. This requires building displacement demands are calculated utilizing peak elastic displacements and drift demands and the resulting overturning moments used to calculate base hinge designs. For taller buildings (≥9 storey's) horizontal shear forces during response are affected by higher mode affects and P-Delta should be considered.

NZS 1170.5 – Code Loading Requirements
The seismicity requirements outlined in NZS1170.5 are to be followed with selection of appropriate Z, R factors. For load bearing frames Sp=0.7 and ductility factor (μ) of up to 4 is considered relevant. For non-load bearing Sp=0.7 and higher values of μ maybe acceptable, providing the engineer can demonstrate the frames rocking response (during SLS seismic or ULS wind) does not cause any unacceptable damage to fitout, services facades or limit the use of the building.

Software – for analysis and detailing
For design, the CRSBF structure or building may be modelled with 3D software such as ETABs. The models must include all material properties, seismic weight (DL, SDL and ΨIL), at the time of the seismic event. Analysis methods shall consider both equivalent static and modal response spectrum analysis methods using CQC. Our approach has been to consider μ=1, Sp=1 for elastic response with scaling of actions undertaken outside of ETABs or within load case combinations. Models shall appropriately represent base fixity or pinned base conditions, relevant in response up to the point of rocking initiation. Modelling of "during" rocking response such as compression of springs or stretching of post tensioned cables and yielding of UFP plates/friction devices is complex and separate analysis are recommended to determine their contributions.

Software – for verification
Whilst outside the recommendation of the SCNZ guideline, if required for verification purposes, upon completion of the primary design a nonlinear time history analysis, with appropriate parameters for ringfeder spring stiffness's utilising gap or spring elements and appropriate consideration for foundation vertical stiffness may be modelled. Aurecon have often used SAP2000 for this purpose, but there are other suitable suites with relative advantages and disadvantages. In our experience a multi-linear elastic link has demonstrated the reasonably reliable behaviour, reflective of a controlled rocking hinge observed in testing, with parallel friction hinges providing resistance. Critically care is required to selecting and accurately scaling appropriate earthquake input records to be compliant with the intent of NZS1170.5.

The author notes that due to limited experience modelling these aspects this complex tasks is often a source of inconsistency. Consultants are encouraged to collaborate with SCNZ or other experienced consultants in developing suitable and reliable NLTHA models that accurately exhibit rocking behavior. NLTHA should be used as a validation tool or bounding analysis to ensure the design analysis is reliable. There are many references and sources the reader may refer to ensure their modelling is giving appropriate results. This process whilst very complex and detailed is useful to validate the NL aspects of rocking response in terms of contact bearing, out of plane response and resistance generated from floors and UFP's.

Analysis of Floor Diaphragms

These elements are considered as rigid, elastic systems with limited/nil out of plane stiffness and hence a separate planar diaphragm analysis (from seismic modelling) is required for design. Engineers are recommended to review this aspect and ensure their structural configuration achieves this objective. Rational methods for diaphragm analysis via strut and tie analysis as recommended by NZS11as recommend by Bull et al and Clifton et al. Care is required to ensure inertial forces and transfer forces are understand. Transfer force affects from rocking frame bearing on shear keys at floor levels can be significant.

Considerations of peak displacements

Peak lateral displacements shall be estimated as per section 7 of NZS1170.5, based on fixed base response, prior to rocking response. These are achieved by modifying the elastic displacements by μ and by a modification factor of 1.3. This factor is based on research conducted by Sause in 2006. As a result drift modification factor K_{dm} is not considered necessary.

Considerations for Higher mode affects

Higher modes are estimated using the truncated response spectrum analysis, based on C(T) with ordinates of zero for periods longer than the second translational period. These modes are then combined with the prime modes using CQC combinations in ETABs. Care is required with sign conventions when using these methods. The modal response spectrum methods requires use of combinations which include and exclude torsion.

Torsion

Torsion shall be considered as required by NZS1170, untaken by offsetting the center of mass and rigidity by 0.1b via movement of the mass method, included within the higher mode analysis. These actions must be accurately attributed to the bracing frames in combination with prime mode response.

Vertical Acceleration during or following rocking

The work by Wiebe et al to date has demonstrated that column impact loading following rocking is transient in nature and does not affect column axial forces. More research is being conducted in this area.

5.0 - Detailing Guidance

This section offers high level considerations for detailing the key components of CRSBF's. In addition it provides images of similar examples and projects

Foundation and CRSBF connections

The purpose of the base connection is to provide robust and dependable compression and bearing foundations that can adequately resist the total rocking axial force, delivered via a single column. Horizontal CRSBF shear loads maybe introduced to the foundations via a central shear key or 'bump' stoppers around cast in steel frames embedded into the foundations beneath each column leg. Vertical CRSBF column uplift or net tension loads can be applied to the foundations via post tensioned anchors or tuned down rods anchored through baseplates and ringfeder springs. The detailing requires shear transfer mechanism for contact compression, bearing, tension and shear at the base connection as outlined below.

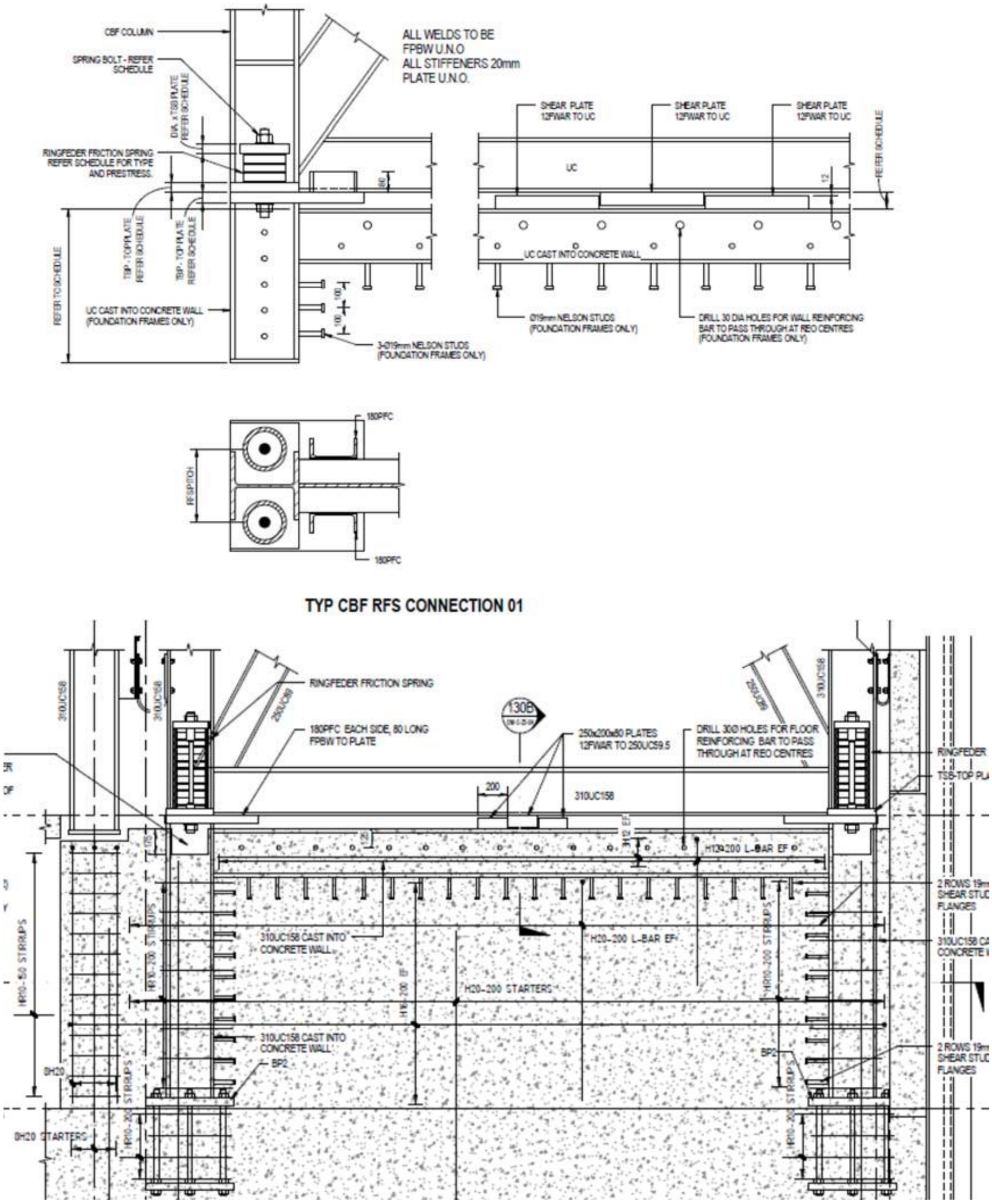


Figure 5 – CRSBF connection to foundations and cast in steel frame components.

Base Rocking Hinge
The base rocking hinge provides resistance to uplift via supported weight, friction and post tensioned squash. The following drivers affect the design of the base rocking hinge.

The structural performance of the base rocking hinge shall include contributions from weight, supplemental energy dissipation, and any post tensioning. Size, capacity, durability and seismic performance (stiffness) are key considerations for energy dissipaters. Architectural considerations include – space, size, future access for repair and maintenance.

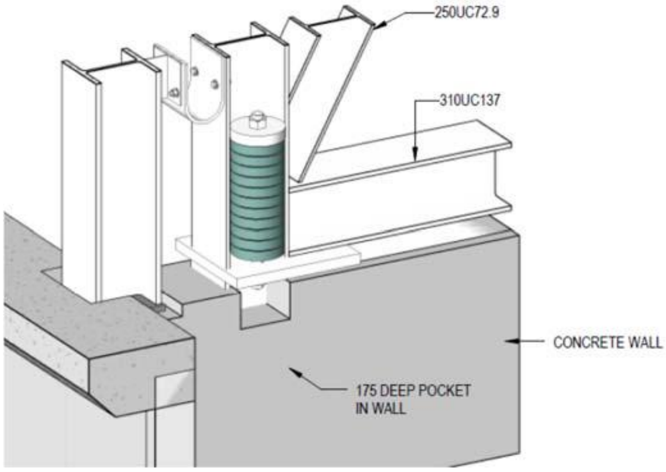


Figure 6 – Base Rocking Hinge – Ringfeder springs, cap plate and turned down anchor bolt with UFPs

Energy Dissipation Devices
These need to be regular, reliable, not too expensive to install or maintain, durable provided by;

- Ring feeder Springs – more information can be found from http://www.ringfeder.com/en/international/products/ringfeder/Product/?p=4812 or from the Australian Suppliers Statewide Bearings in Australia. A detailed schedule of springs, cap plates and tensioning is required to inform manufacturer and installers of the engineer's requirements.

RINGFEDER FRICTION SPRING SCHEDULE													
TYPE	OUTER SPRING TYPE	OUTER SPRING ELEMENTS	INNER SPRING TYPE	INNER SPRING ELEMENTS	PRESTRESS %	SPRING BOLT DIAMETER	TURNED DOWN LENGTH	TURN DOWN PLUS TRANSITION	PLATE THICK TBP mm	PLATE THICK TSB mm	RFS PITCH	HEIGHT OF SPRING	HEIGHT OF SPRING AFTER PRE-STRESS
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS02	24201	22	19600	20	50	60-46	410	430	50	50	290 mm	600.6	542.3
RFS03	24201	22	19600	20	50	60-46	410	430	50	50	300 mm	600.6	542.3
RFS03	24201	22	19600	20	50	60-46	410	430	50	50	300 mm	600.6	542.3

Figure 7- Typical project specific Ringfeder Installation Schedule

- Post tensioning (PT) anchors for self-centering - full height or localized to base rocking joint. These require access for installation, anchoring, maintenance and potential re-tensioning at the top of the CRSBF.

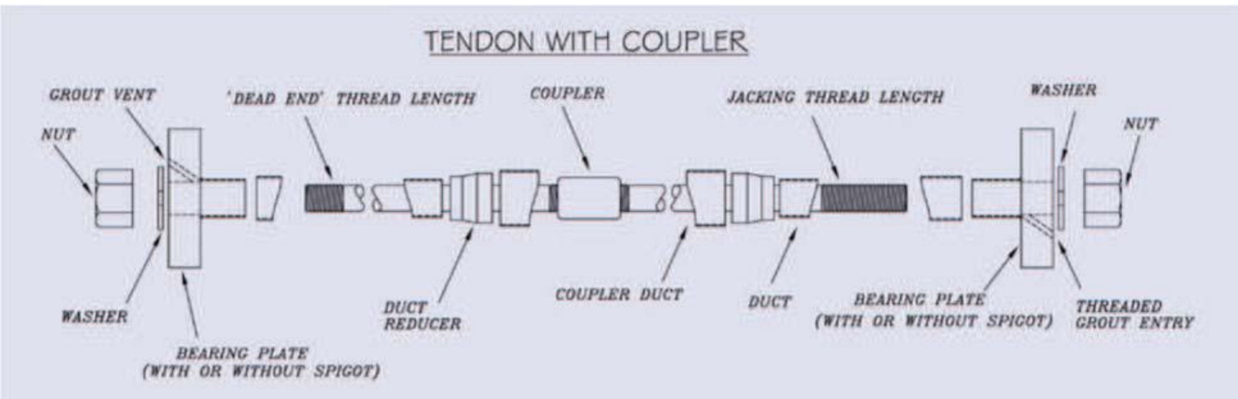


Figure 8- Macalloy PT Tendon – Vertical Post tensioning (Courtesy – Macalloy)

- Asymmetrical or symmetrical friction connections – Refer to recent UoC and UoA project thesis on AFCs and Sliding hinge joints for more information. SCNZ and HERA also have a significant body of information on this topics. These require to be enclosed within the weather proof envelope, require special detailing including high hardness (Bisalloy 400 or greater) shims and plates to ensure reliable friction surface in response to uplift and restoring compression.

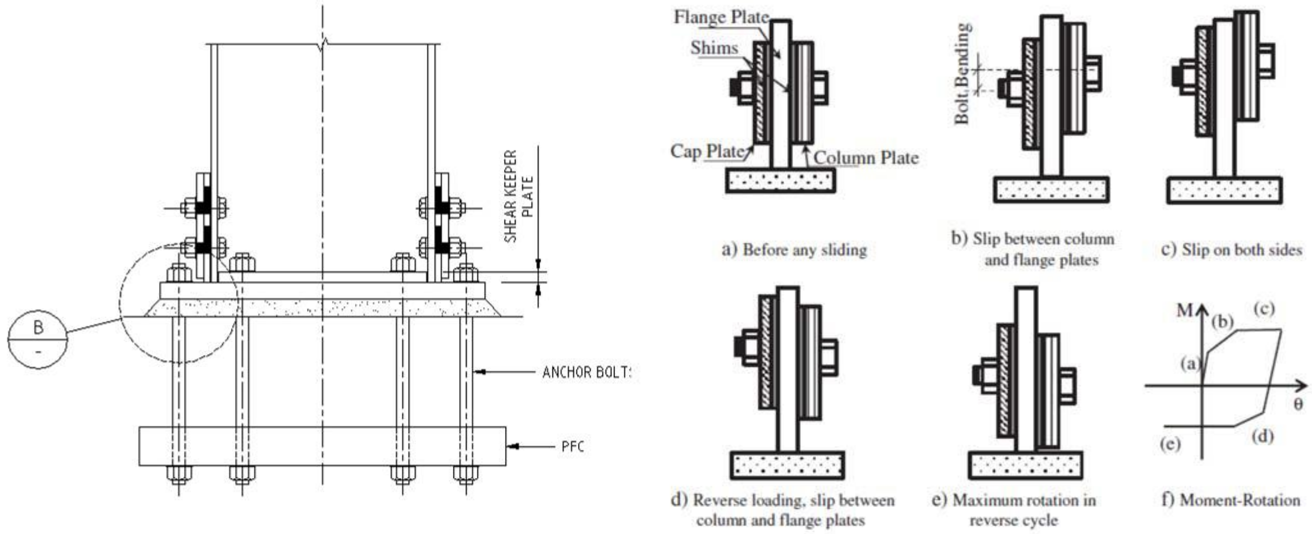


Figure 9 - AFC Friction Base Connection, Te Puni student Village and AFC friction plate section and hysteresis (Source Bourzie et al, 2015).

- U-shaped flexural plates (UFPs) – These are intended to be bolted between rocking frame columns and adjoining orthogonal walls or gravity only columns. The plates and their fixings require space around to bolt in and unbolt post event should they ever become damaged or exceed strain limitations.

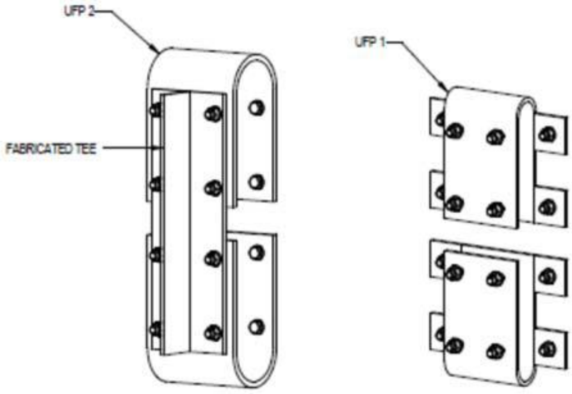


Figure 8 – U-shaped flexural plates – connection between rocking frames and adjacent gravity or walls

Structural Connections –CRSBF to rigid floor diaphragms

- Diaphragm connections (shear keys) between the CRSBF and floor systems must be capable of receiving the full elastic strut or tie force components from building or frame displacements at each floor level. Shear key elements relying on concrete bearing forces must be sized to limit contact stress to less than 0.4F'c in compression and 1MPa in tension. The details must allow adequate tie anchorage, floor to steel connections and where required provide out of plane restraint.

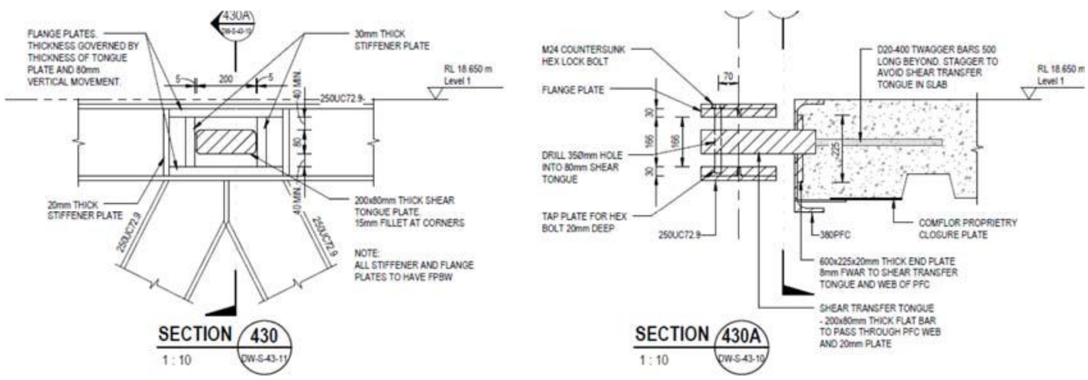


Figure 10 – Rocking Frame Floor Level shear key connections

CRSBF – Articulated Column to adjacent Gravity column/floor connection
During rocking, the MCE vertical uplift of the rocking column must able to occur without imparting damage on adjacent floor and gravity columns. The connection must be robust and able to maintaining the peak shear/ tension resistance to deliver the full elastic node forces imparted from the seismic diaphragms. The below detail provides an example of how this can be achieved with high hardness shims and large diameter bearing pins through captive plates and a fabricated slot in the rocking column.

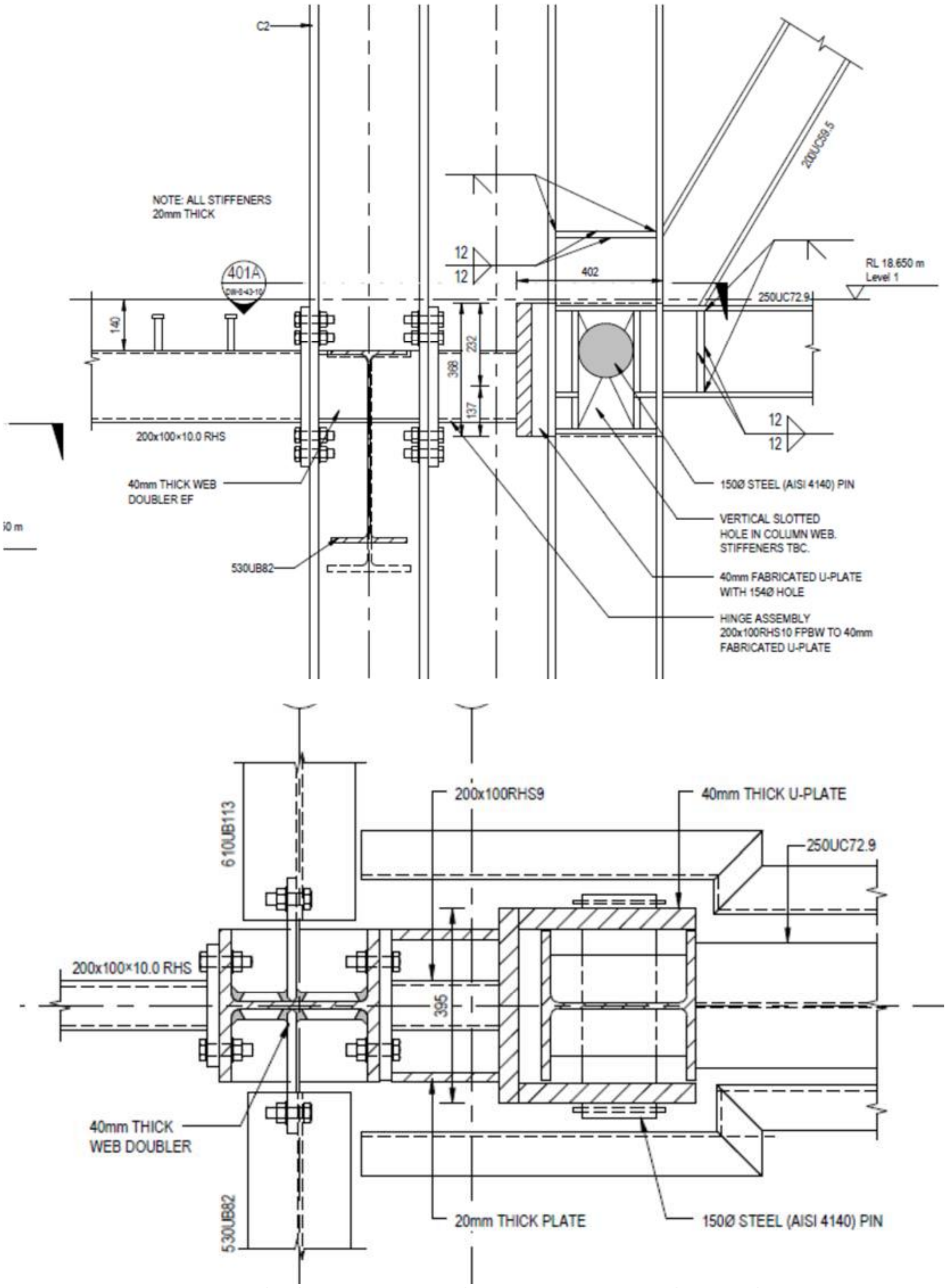


Figure 11 – CRSBF – Rocking Column to adjacent Gravity Column.

CRSBF Components – Concentrically braced frames – columns, collectors, braces
Frame member connections are ideally bolted on larger frames for ease of installation. Welds and bolted connections must ensure the frame responds elastically during rocking up till full base rocking joint. At this point (typically MCE response) some localised inelasticity may be accepted, depending upon the design brief and expectations.

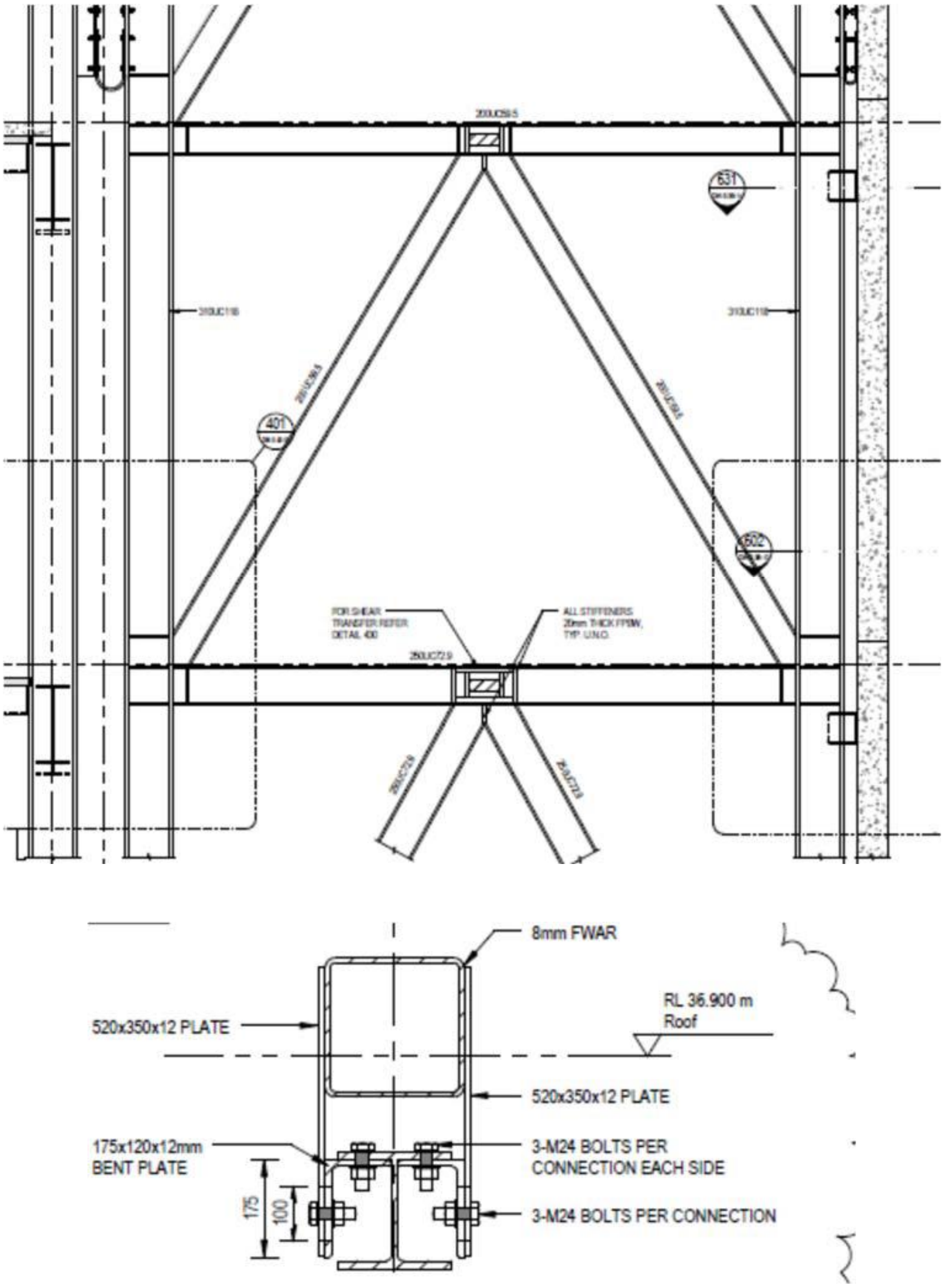


Figure 12 – CRSBF – Frame Elevations.

6.0 - Lessons learnt

There are many benefits of using CRSBFs, designed and detailed following the above guidelines and as outlined in more detail in SCNZ's "Design Guideline for Controlled Rocking Steel Braced frames" report 110; 2015. These include;

- The CRSBF is a reliable structural system with damage and ductility placed in replaceable parts and components.
- Elastically designed steel frame – design to strength of base rocking joint. Elastic response of members improves reliability as positive stiffness of elastic frame
- The rocking base hinge reduces column tension and foundation demands limited to the strength of the turned down anchor bolts or the yield strength of the post tensioning anchor bars
- Stiff due to– targeting low drifts and peak displacements
- Initial uplift resistance can be reliably provided from friction connections or UFP plates
- Rocking should not be relied on alone to provide energy dissipation. Reliable energy dissipation should account for at least 40% of the base rocking hinge moment, provided by Ringfeder Springs or full height post tensioned anchors
- Load bearing rocking frames have very similar architectural and fitout detailing requirements to traditional ductile systems. Non load bearing systems require higher post tensioning forces and initial uplift resistance due to less self-weight in the system
- Low structural damage solutions can be achieved – focused energy dissipation into replaceable U-shaped flexural plates, sliding friction connections and turned down" mild steel anchor plates
- High performance structural system for reasonable cost
- controlled rocking can avoid primary frame damage
- higher modes dominate member design forces for taller frames
- Column impact does not seem to cause major structural issues if the gravity load is small

Challenges for the use of the CRSBFs

The challenge of early adoption is the extensive learning, research, testing and development that has occurred over the last ten years within Aurecon and at UoC and UoC. In implementing the technology it has create several unique challenges that once overcome will ultimately benefit the engineering and construction industry.

Architectural/planning and design

- The CRSBF introduces complexity at ground level at the interface between rocking frames and cladding junctions of load bearing rocking frames. Lintels and mullions are needed to create voids around non load bearing systems.
- Façades and detailing for building drifts – these tend to be the same or lower than traditional structures. The main difference is that at ground level, the column base plate may uplift meaning facades and curtain wall systems are best suspended from lintels or whalers to ensure these don't accidently prevent uplift or are damaged during SLS events.
- Planning – CRSBF need to be located near the exterior of perimeter of buildings. This ensures not only are they best positioned to engage with floor systems, but at the rocking base, their hinge device can be easily inspected and repaired post event. It's important that selected locations for access, maintenance and post event repair
- CRSBF should be located to have the least effect on architectural planning and spatial use. Ideally the frames have suitable aspect ratio (H/W), connection and are built either exposed on the perimeter of a building or within atrium/cladding lines. A roof level consideration of movement means care is needed around cladding, waterproofing, durability considerations, to ensure that frame movement doesn't damage these features during low level events
- Planning for installation of ringfeder springs - Ringfeder springs are typically located within the web/flange recess of main structural columns of the CRSBFs. These are then seated on thick baseplates and stressed down vertically to foundation systems. It's important to allow adequate space for these plates, springs and endplates. These items can occupy significant space and may even require increasing column section sizes to enable installation.
- Detailing for movement – it's important to understand the expected movements and brief design partners such as architects and builders so that they understand any limitations of what they can and can't fix to the CRSBFs.
- Major design challenges may include:
    - Frame connection detailing
    - Frame connections to diaphragms
    - Mitigating higher mode effects for taller frames
- Services considerations – connections, joints, fixing to CRSBF need to consider expected and relevant movement. As above these are significantly smaller than seismically isolated buildings and are comparable or less than traditional buildings.

- Fire – performance and installation of fire collars needed around non load bearing columns of CRSBF may require seating plates and intumescent paint.

Construction/fabrication

- Structural steel detailing/Weld detailing – due to the expected rotation, welded joints need to enable articulation. CRSBF typically have bolted and welded joints. Care is needed in the design and detailing of the main columns in particular the detailing of slotted connections that enable uplift without requiring significant heavy FPBW to columns as reinforcing or armoring. Any column splices must achieve 100% bearing without slippage as this will affect the rocking frame behaviour. In addition care is needed to ensure the baseplates, endplates and shear transfer mechanisms all have sufficient capacity to reduce high forces developed during rocking. Where possible consider appropriate welds for the function needed and try to reduce costs by reducing volume of any full penetration welding.
- Post tensioning cables installation – these need to be located within full height ducts, couplers and space for their installation, tensioning and potential future re-tensioning. Safety considerations of bonded vs unbonded tendons should be made for those who may be involved in the buildings future post event recovery or demolition.
- Installation of post tensioning systems Depending upon the selected Ringfeder size, for installation of the springs and adding pretension (compression) the fabricator/installation will need substantial hydraulic enerpac equipment or a welded gusset plates and stiffeners for a direct push hydraulic jack. Depending on the selected springs, to provide 50% preload, these may require up to 150-200tonnes pressure.
- Durability detailing – If Ringfeder springs are used these must be housed in a durable non porous boot to house the low friction grease
- Cost/complexity of CRSBF fabrication coupled with supply and installation post tensioning and Ringfeder springs are comparable to seismic isolators. However a CRSBF does not require a subbasement or significant cantilever columns and isolation plane to function.
- Post event access, checking/repair – it’s essential that the frames and the parts and components that may be damaged be located in places of easy access. This is critical to reduce the cost of loss of operation and repair necessary to inspect CRSBF following a design level or larger earthquake.

7.0 Future research needed

Research to date

Professor MJN Priestley stated in his 1978 paper “one of the key benefits of structures allowed to rock on their foundation is that the forces are somewhat limited to the force at rocking. In addition structural damage can be reduced or limited by designing the bracing frames to remain elastic during rocking response”. This philosophy still underpins the basis of CRSBF design.

As summarized by SCNZ’s CRSBF Design Guideline there is a significant body of research into rocking structures. The work has been ongoing by several leading researchers since the late 1970’s and there is clearly still more to learn and understand.

Recent research has focused on floor system interaction, benefits of nonlinear braces, and benefits of additional rocking hinges.

Future Research focus areas

In the authors opinion more work is will benefit design engineers in considering the following areas in more detail;

- The effect of foundation instability on CRSBFs
- Cost effective methods of reducing floor acceleration in parallel with CRSBFs
- Benefits of additional energy dissipation in the design of CRSBFs
- Cost affective CRSBF connection design
- Reliable base shear transfer mechanisms
- How to harness CRSBFs to improve the performance of non-structural systems – facades, contents, ceilings?
- Influence of slab OOP affects and how to design these connections for enhanced reliability
- Using CRSBF systems in dual or orthogonal bracing direction

8.0 Conclusions

The paper presented key concepts of Controlled Rocking frames, outlined performance objectives, and identified a design process. In addition the paper has made some observations and provided commentary on the analysis and verification process for the design of CRSBFs. The paper has explored key aspects of structural steel detailing and design, outlined lessons learnt and benefits/challenges of deploying CRSBFs on recent projects.

The paper has not identified formulae or sensitive parameters and instead has made extensive reference to SCNZ's "Design Guideline for Controlled Rocking Steel Braced Frames" report No 110; 2015, and the author encourages the reader to review in detail, alongside the references outlined therein.

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