

INNOVATIVE USE OF BUCKLING RESTRAINED BRACES AT THE UNIVERSITY OF AUCKLAND

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ABSTRACT

Buckling Restrained Braced Frames (BRBF's) are a recently developed structural system, and consist of Steel Frames incorporating concentric Buckling Restrained Braces (BRB's). BRB's are characterised by almost equal capacity in compression and tension, and a high degree of post-elastic reliability.

BRB's comprise of a mild steel core confined within a steel hollow section by a grout infill which restricts Euler Buckling. The steel core is isolated from the grout infill to allow it to act independently of the grout, and consists of a yielding region and an elastic region.

BRB's were originally developed in Japan by Nippon Steel Corporation and have since been developed further as proprietary items in USA by two further companies, StarSeismic and CoreBrace. Considerable testing of these proprietary items has been undertaken by the manufacturers. BRB use in New Zealand has been limited to date, with the authors aware of at least two examples.

Beca Carter Hollings and Ferner Ltd (Beca) are currently in the process of designing two projects at the University of Auckland which utilise BRB elements sourced from USA. The projects are the B403/404 Faculty of Engineering and B302 South Tower. The B403/404 Faculty of Engineering is a retrofit and extension of an existing four-storey reinforced concrete frame structure with six additional floors provided. The B302 South Tower is a new twelve storey steel structure on the retained foundations of an existing three storey podium building. BRB's are proposed to be adopted for these buildings to act as a stiff, reliable structural system that limits non-structural damage, and in which structural damage is concentrated in discrete, replaceable elements. This paper discusses the general principles used in the design of BRBF's and the approach taken in the design of these structures.

KEYWORDS: Buckling Restrained Braces, Beca Carter Hollings and Ferner Ltd, StarSeismic, CoreBrace, Unbonded Brace, Design Considerations, Comparison of manufacturers.

Introduction

Buckling Restrained Braced Frames (BRBF's) are a relatively new type of concentrically braced frame system that uses steel braces capable of inelastic yielding in both tension and compression.

Beca Carter Hollings and Ferner Ltd (Beca) are undertaking the structural design of two new projects at the University of Auckland which incorporate BRBF's as the main lateral load resisting systems.

This paper outlines the components and characteristics of a BRB, a discussion on the US based proprietary manufacturers and a brief description of the BRBF systems proposed for the two University of Auckland projects, the B403/404 Faculty of Engineering and the B302 Science Centre South Tower.

This paper is intended to provide designers with an outline of the issues which must be considered in the design of a BRBF structure in New Zealand conditions

ANATOMY OF A BRB

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The concept of buckling restrained braces was originally proposed in Japan in the late 1980's. The initial system consisted of steel plates 'sandwiched' between precast concrete panels to suppress buckling. This developed into use primarily as hysteretic dampers within moment-resisting frame structures. Subsequently, BRBF's were further developed in the United States as a bracing element utilising a core of un-bonded steel which can yield in both tension and compression. This core is surrounded by grout contained within a steel SHS or CHS element that restrains the inner steel core from buckling under compression loads. Considerable research and testing has been undertaken in the late 1990's and early 2000's with three specialist BRB manufacturers now offering proprietary patented systems in the USA. The first building in the USA to use buckling restrained braces was constructed in 2000. By the mid 2000's nearly 30 projects were either complete or underway in the USA. Design guidance for BRBs has recently been developed in the USA with various design guidelines and publications prepared (for example SteelTIPS [1], and AISC Seismic Provisions for Structural Steel Buildings [2]). Use of BRBF's in the USA has become increasingly popular with the number of projects completed or underway in the USA now understood to number approximately 200.

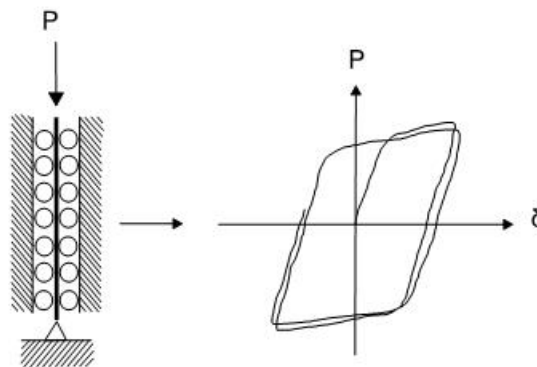


Figure 1. Diagram indicating principle of BRB [1]

BRB's are suited for the cyclical loading that braces experience during a seismic event. By yielding in compression as well as tension the braces are able to dissipate large amounts of seismic energy. The compressive capacity of the braces can be closely matched with the tensile capacity, with the compression capacity slightly higher than the tensile capacity.

An inner, relatively slender, steel core is encased in grout and an outer steel tube. The inner steel core carries the loads, and the function of the grout and steel tube is to act as a restraining mechanism for the steel core to prevent buckling that would normally occur under large compressive loads. Special consideration is required to the interface between the core element and the concrete as it is important that the inner core does not adhere to the concrete. Similarly, the inner core member cannot be confined in such a way that it is unable to yield. In order to prevent adherence, ensure proper confinement and understand the braces' behaviour, full-scale braced systems have been tested by the various manufacturers.

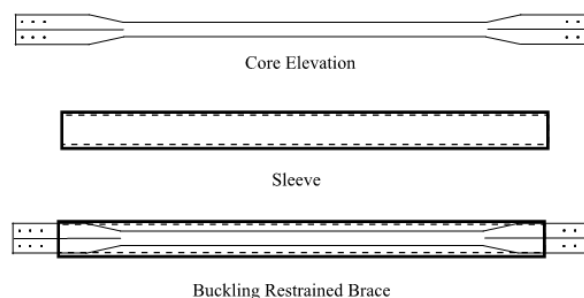


Figure 2. Components of a Buckling Restrained Brace

Use of BRBF's in New Zealand has been very limited to date. It is understood that two projects have been designed to date, but the size of project and brace capacities required by these projects are understood to be considerably less than what is required for the University of Auckland B403/404 and B302 projects. Currently, the New Zealand Code does not include specific design provision or guidance on BRBF's. However, design guidance from the US and Canada can be adapted for use with the New Zealand Building Code. Early agreement on the design methodology with an appropriate Structural Peer Reviewer and the local Territorial Authority is recommended in order that the Building Consent process for the project is not

adversely affected.

BRBF Advantages

Significant advantages are seen to be available from the use of a Buckling Restrained Brace system.

- Braces can be designed for controlled strength and stiffness.
- BRBs are lightweight, compact elements which can be designed and detailed with a variety of end connection configurations (pinned, welded, bolted).
- BRBs have a high ductility capability and can reliably withstand significant seismic actions. The actual level of ductility required for the brace by the design can be limited which potentially provides a significant reserve in seismic performance for an earthquake greater than the design level event.
- Damage in a seismic event is concentrated in the BRB element (effectively acts like a “fuse”). The BRB element can if necessary be replaced after a major seismic event.
- Depending on the configuration used, BRBF’s can give lower foundation loads than comparable shear wall systems.
- Smaller steel column and beam sizes result from the use of a braced frame rather than a moment frame structure.
- A BRB system is cost competitive compared to other structural systems. Multiple manufacturers gives the possibility of a competitive tender process being used.
- While manufacture of the actual BRB element itself is best undertaken by a specialist supplier with a proven track record of supply and with appropriately tested and certified componentry, the actual installation of the BRB elements themselves can be undertaken by any competent local structural steelwork erector.

As noted above it is considered that BRB braces are particularly suited as the seismic load resisting systems for these structures, as it allows a reduction in seismic loads due to high ductility capacity and hence less strengthening work required to existing foundations.

PROPRIETARY MANUFACTURERS

Although BRB’s were originally developed in Japan, these are most likely to be purchased as proprietary items from USA.

StarSeismic LLC

Star Seismic are based in Park City, Utah, USA. They are able to provide Pinned (Powercat™ BRB), Welded (Wildcat™ BRB), and bolted connection configurations. StarSeismic braces are manufactured in Salina, Kansas and Salt Lake City, Utah.

StarSeismic is unique, in that the core steel for the BRB is manufactured from ‘Bar Stock’ rather than being cut out from plate. As a result, the lead time for material procurement is potentially reduced.

The cores are shaped like a large tensile test coupon, and to increase the core area, multiple cores are used side by side. The core is separated from the grout by a physical gap. Another feature of StarSeismic braces is the ‘collar’ which prevents undesirable buckling behaviour of the connection.

For large braces, the system can be used in a modular fashion, where up to four braces can be used side by side, connected by a common end plate and a proprietary collar.

See below link for access to StarSeismic website:

<http://www.starseismic.net/>

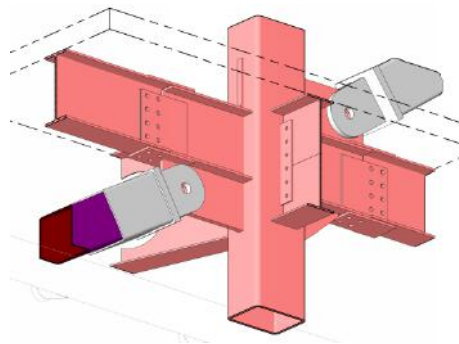


Figure 3. Revit image of a proposed StarSeismic pinned connection detail.

CoreBrace LLC

CoreBrace are based in Salt Lake City, Utah, USA and are a 'sister company' of SME Steel, which is a large Steel Fabricator in USA. CoreBrace are able to supply Pinned, Bolted Splice, Bolted Lug and Welded connection configurations. CoreBrace BRB's are manufactured at the same location in Salt Lake City. CoreBrace steel cores consist of a fabricated 'cruciform' shape, which are separated from the grout material by a 'separator medium'.

See below link for access to Corebrace website:

<http://www.corebrace.com/>

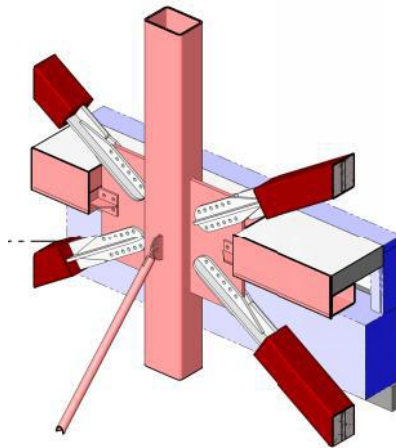


Figure 4. Revit image of a proposed CoreBrace bolted lug connection detail.

The Unbonded Brace

Unbonded Brace™ is the product of a consortium of companies. These companies are:

- Nippon Steel Engineering Co. (Original developer of the buckling-restrained brace concept and holder of two BRB patents. Main office in Tokyo, Japan with satellite office in San Mateo, California, USA).
- Mitsui & Co-USA, Los Angeles, California, USA (Business and logistics agent).
- Seismic Isolation Engineering, Oakland, California, USA (Technical consultants).
- Yajima Inc., Tokyo, Japan and Reno, Nevada, USA (Exclusive manufacturer of Unbonded Braces™).

Unbonded Brace™ is available in Welded, Pinned, and Bolted connection configurations.

Unbonded Brace™ is designed and manufactured with a 'cruciform' shape or 'flat' core, separated from the grout material by a 'separator medium'.

Nippon Steel Engineering Co. estimates that there are more than 300 buildings employing Unbonded Braces in the Fukushima, Iwate, Tochigi, Saitama, Chiba, Tokyo and Kanagawa prefectures - all which experienced 4-5 minutes of strong shaking in the M9.0 Great Tohoku Earthquake. To their knowledge there were no failures in these structures with the braces all performing well.

See below link for access to the Unbonded Brace™ website: <http://www.unbondedbrace.com/>



Figure 5. Unbonded Brace™ connection in an exterior exposed application

Testing Procedures

Extensive testing of BRB's has been undertaken in USA, including uniaxial tests and sub-assemblies. Testing procedures are described by AISC 341[2] and FEMA 450[3].

UNIVERSITY OF AUCKLAND PROJECTS

Beca are currently undertaking the structural design of two significant projects at the University of Auckland City Campus that utilise BRBF systems.

B403/404 Faculty of Engineering

The proposed B403/404 Faculty of Engineering building is located on Grafton Road on the University of Auckland central city campus. The proposed building is a 10 storey structure which comprises 6 new storeys on top of an existing 4 storey concrete frame and shear wall structure. Refer to Figure 6 for 3-D structural perspective.

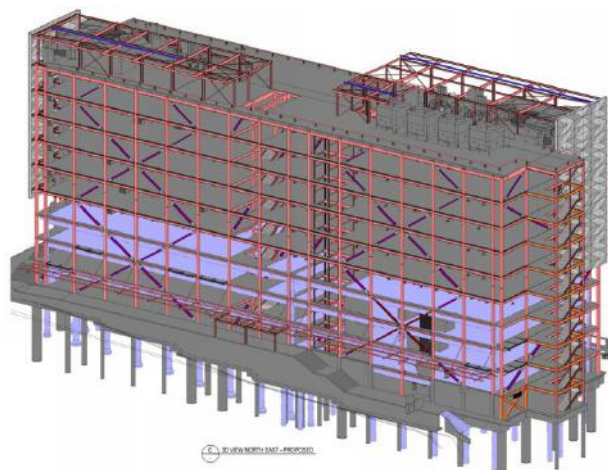


Figure 6. REVIT model 3-D perspective of proposed B403/404

Existing Structure

Buildings 403 and 404 are reinforced concrete structures that were built in the early 1960's. Building 403 has three existing suspended floors (levels 3, 4 and 5) and Building 404 has four existing suspended floors (levels 2, 3, 4 and 5).

Buildings 403 and 404 have three rows of reinforced concrete frames located on the external façade lines and central grid to provide lateral load resistance to the buildings in the longitudinal (north/south) direction. These frames also provide the gravity support to the floors within the buildings. Lateral load support in the transverse (east/west) direction is by means of a pair of shear walls, one at each end of both the buildings. The foundations for both buildings comprise cast-insitu, reinforced concrete piles, which are belled at the base. There are a series of ground-beams connecting these piles at ground level.

Proposed Structural System

It is proposed that a new “BRBF exoskeleton” steel frame be erected largely on the outside of the existing building envelope to support the vertical and lateral loads of the new floors above. The new central steel columns supporting the new levels 6 and upwards are supported on the existing central reinforced concrete columns. Strengthening of these existing reinforced concrete columns will be required to support the increased gravity loads of the additional floor levels.

The steel exoskeleton is configured in ‘single diagonal’ BRB arrangement to reduce demand on collector beam elements. The bracing system will reduce demand on the existing concrete longitudinal moment frames and reduced shear walls by limiting the drift of the structure. Refer to Figure 7 for Revit image of proposed connection detail. The BRBF elements span large widths of the building (up to four bays) with the result that the foundation loads under lateral loading is reduced compared to the foundation loads imposed by a shear wall system. This allows the existing piles to be re-used as much as possible with new piling works being kept to a minimum. The transverse BRBF’s are located approximately 1.7m outside the existing building envelope, simplifying installation of the new piled foundations.

Two internal braced frame lines have been added either side of the central circulation space to allow some flexibility for creating floor voids for stair structures and architectural visual connectivity between floors. The location of these internal bracing lines has also been positioned to avoid the external longitudinal BRBF’s. This avoids the requirement for external columns supporting lateral loads from two principle axes concurrently. Another advantage of the proposed BRB frame configuration is that they are evenly distributed horizontally and vertically, minimising torsional behaviour.

One potential issue that has been identified is the lower half of the structure is exposed externally, so particular attention is required for durability aspects.

The brace capacity in this structure varies from 3000kN to 330kN for ULS, with an overstrength capacity for the largest brace of approximately 4500kN. The casing size varies from 350mm square to 200mm square.

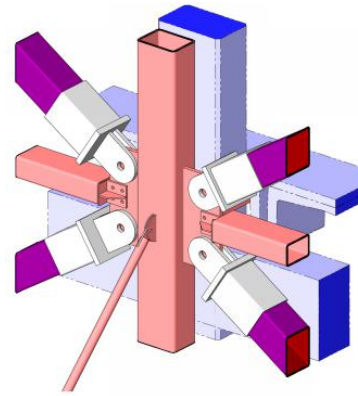


Figure 7. Revit model image of proposed ‘exoskeleton’ connection detail.

B302 South Tower

The proposed B302 South Tower building is a new 12 storey structure located on the corner of Symonds Street and Wellesley Street East on the University of Auckland central city campus. Refer to Figure 8 for 3-D structural perspective.

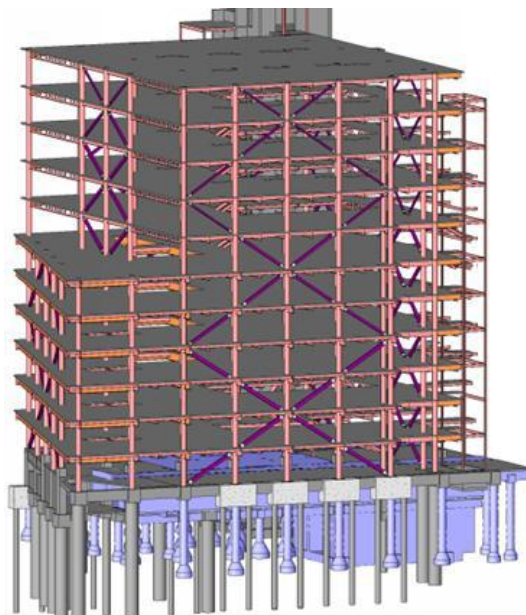


Figure 8. REVIT model 3-D perspective of proposed B302.

Existing Structure

The existing Science Centre South Tower superstructure consists of a two way concrete moment frame, with a concrete shear wall substructure. The superstructure is proposed to be demolished down to ground level, with the foundations and basement to be retained (areas in blue shown in Figure 8) for use in the new B302 structure.

Proposed Structural System

The new B302 structure will consist of concrete composite metal decking supported by long span cellular beams. These are in turn supported by welded steel columns on a combination of new and existing foundations.

Similar to the Faculty of Engineering, a single diagonal BRBF will be used as the primary lateral load resisting system in both the transverse and longitudinal directions. The bracing layout spreads loads over four structural bays which has the benefit of decreasing foundation loads due to a larger lever arm. This configuration has the added benefit of simplifying connections, as brace loads can be directly transferred to the next brace, rather than transferring through collector beams.

The proposed BRBF's are evenly distributed around the perimeter of the structure to reduce torsional behaviour, and similar to B403/404, the BRBF's in the transverse and longitudinal directions do not have common columns to avoid increased loads through concurrent actions.

One particular issue with the proposed BRBF configuration is that the structure is exposed internally, and to minimise the impact on internal building layouts the gusset connections have been shaped to reduce the overall size of the connection, see Figure 9.

The brace capacity in this structure varies from 4200kN to 600kN for ULS, with an overstrength capacity for the largest brace of approximately 7000kN. These very large forces result in large connection details at the foundation level.

The BRB casing size varies from 350mm square to 200mm square.

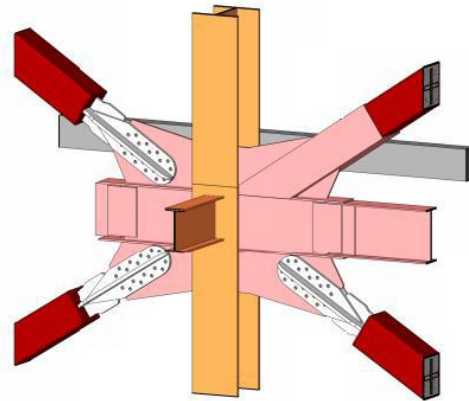


Figure 9. Revit model image of proposed BRB connection.

DESIGN CONSIDERATIONS

The following items were encountered during the design of these projects.

Code Compliance

As the New Zealand design standards do not recognise BRBF's as a structural system, they must be designed as an 'Alternative Solution' as per the New Zealand Building Code, utilising the US code provisions. These include:

- ASCE 7 [4].
- FEMA 450 [3].
- AISC 341 [2].

To assist the New Zealand based peer reviewer, Beca has engaged a USA based recognised expert in the design of BRB elements to provide a specialist review of the lateral load system.

Foundations

Depending on the bracing configuration (i.e. number of braces, width of bracing bays), large concentrated compression and tension loads can be generated in foundations. This may require large baseplate assemblies to transfer forces into piles.

Connection Type

The type of connection used (Bolted/Pinned/Welded) has a significant impact on the BRBF design. The type of connection configuration used imposes various requirements when following the US code provisions, such as:

- Building Height limitations.

- Allowable ductility.

The type of connection used also impacts on the performance of the frame, as it is ideal to have a minimal fixity of the connection. This is because a large rigid connection with a gusset plate can introduce secondary actions into the columns, beams and the brace through frame deflections.

For this reason a pinned connection may be seen to be beneficial, however these also require large gussets so will still have a significant fixity.

Bolted Splice

Bolted splice connections are beneficial in that they are able to be swung into place directly. These are large connections however, with a large number of bolts and splice plates. This type of connection also uses 'TF' type bolts which must be tensioned properly on site.



Figure 10 (left) Example of Bolted Splice Connection (Image provided courtesy of Seismic Isolation Engineering, Inc.) and Figure 11 (right) Example of Pinned Connection.

Pinned

Pinned connections are typically more expensive, and have a very small erection tolerance (~0.8mm). The additional expense associated with this type of connection is due to doubler plates on the brace and gusset to stop the pin tearing out of the plate.

Welded

Welded connections are the simplest type of connection available, and hence most likely the cheapest brace type to manufacture.



Figure 12 (left). Example of Welded Connection and Figure 13 (right), Example of Bolted Lug Connection

Bolted Lug

The bolted lug connection is similar in principle to the bolted splice connection, however only half the number

of bolts is needed. This is because one half of the connection is shop welded to the core of the BRB. The downside to this type of connection is that the brace must be swung into position either side of the gusset, which increases the amount of crane hook time. The gusset itself may also need to be bigger to allow enough tolerance to enable the brace to be swung into position without clashing with the beams or columns.

Damping

While BRB's have a high level of hysteretic damping associated with their performance in the US design codes the beneficial effect of this high level of hysteretic damping is ignored. In the US the building behaviour is therefore assessed on the basis of a standard 5% hysteretic damping response spectrum curve. It is understood that this conservative assumption was adopted for ease in gaining regulatory approval for the system in the US.

Overstrength

The US codes require a 'pseudo capacity design' approach for the design of non-ductile elements in the BRBF structural system. This means that the brace overstrength forces are calculated based on the expected deformation of the braces and the specific back bone curve determined via testing of braces.

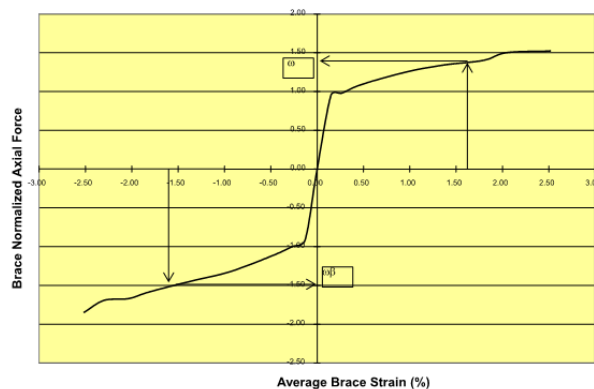


Figure 14. Typical Backbone Curve (provided courtesy of SteelTIPS Document [1])

Elastic vs Non-linear Analysis

An elastic analysis such as modal response spectrum is generally sufficient for the design of BRBF's if following the US code provisions that applies factors to estimate the expected non-linear deformation of the BRB.

If greater accuracy in the estimation of the post-elastic behaviour is desired, a non-linear pushover or time history analysis can be performed.

Constructability

The designer needs to consider constructability aspects of BRBF's, in particular tolerance on bolt hole diameters, brace working point length. There also needs to be consideration of how any issues discovered on site may be rectified, for example how a brace may be modified if it does not fit within the required tolerances.

Post Seismic Event

BRBs are not a "self centering" system which return the building to its original position at the end of an earthquake. However, it is possible to design a stiff structure that may limit any residual offset to an acceptable amount. There may be a possibility of removing the BRB elements and jacking the frame back into position floor by floor following an earthquake event. It is understood that this has not been done on a building to date, however there have been no known issues reported in BRBF structures in Japan following the M9.0 Great Tohoku Earthquake.

Durability

Durability of BRB elements is an important issue to resolve, particularly in a coastal environment such as Auckland. BRBs potentially have components that need special consideration to protect them in external

environments, and the designer is encouraged to discuss this with the BRB manufacturer.

Logistics

There is potentially a long lead time associated with the design and supply of BRB's to a construction site in New Zealand, a range of 14 to 36 weeks lead time for delivery of braces to New Zealand has been estimated by the suppliers for the University of Auckland projects.

Engagement

The designer may consider an early engagement of the BRB manufacturer, as a reduction in lead time may be necessary. Early engagement will allow material procurement to commence and an accelerated shop drawings process. This may however lead to some complicated contractual agreements, and does introduce some risk to the project.

Currency

Exposure to risk associated with foreign currency fluctuations is an issue that should be considered in the project team.

SUMMARY

In summary, BRB's provide superior performance under seismic loads compared to other conventional bracing systems. Because of this, Beca has proposed the use of BRBF's in two significant projects located at the University of Auckland. The BRB's are proposed to be supplied by one of three proprietary manufacturers based in USA. This paper outlines some of the considerations the designer must make in the design of a BRBF structure.

ACKNOWLEDGEMENT

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