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Embrace Your Braces!

Terri Meyer Boake[1]
1 University of Waterloo, tboake@uwaterloo.ca

ABSTRACT

The notion of adaptive reuse can be applied to creating resilience in structures designed to resist seismic events. Many of the issues associated with the difficulties encountered in repairing structures that have been damaged as the result of earthquakes lies as much in the hidden nature of the damage as it does in the repair and remediation of the structures. The structures are not resilient enough to resist the seismic event and are not designed to be repaired. This has been clearly evidenced in the February 22, 2011 earthquake in Christchurch, New Zealand which measured 6.3 on the Richter Scale. Much of the Central Business District of Christchurch is in the process of being systematically demolished as a result of the inability to repair the extensive structural damage.

Christchurch has provided a large test field to examine structural performance during a significant quake event. This seems to point to the benefits of using steel bracing systems over traditional concrete framing systems from the perspective of ease of repair. This in turn has led to suggestions that exposing the braces can make inspection and repair post quake more efficient and effective.

This paper will examine a range of bracing systems towards the promotion of developing an architecture that exploits the exposure of bracing systems to simultaneously answer the needs of seismic (or other severe lateral loading) events through highlighted expression of the bracing system.

Key Words: braced systems; seismic design; steel bracing; eccentrically braced frames; diagrid; exposed bracing; replaceable link bracing systems.

1. INTRODUCTION

The examination of the massive amount of destruction in Christchurch, New Zealand following the recent earthquake on February 22, 2011 provides an excellent “real world” test for the ability of contemporary structures to resist seismic loads and allow for post-event repair. Of the close to 1,600 buildings in the Central Business District of Christchurch that have either been demolished or are in queue for demolition, it was evident that the failure of reinforced concrete structures exceeded the failure of steel structures. Not only were the structures incapable of resisting the forces, the type of damage suffered was impossible to repair, making reuse or adaptation of the structures impossible. The structural problems were hidden within the frames, slabs, columns and walls. The only safe and economic solution was to demolish and build new.

Where some historic structures, such as the Christchurch Cathedral, might provide a compelling case to spend an economically illogical amount of additional funds to repair and restore, the majority of reinforced concrete buildings were constructed during the 1960s and 1970s and might be accused in current design circles of having limited architectural merit. The larger commercial buildings that have survived used steel as their framing system. The tallest tower in Christchurch, albeit only 23 storeys, that has recently had its steel bracing frame repaired is well on its way to being ready to resume its full use.

The large scale demolition of the damaged concrete buildings produces material for recycling, but nothing more. To witness buildings that on the surface might appear to be intact, being demolished, is extremely depressing.

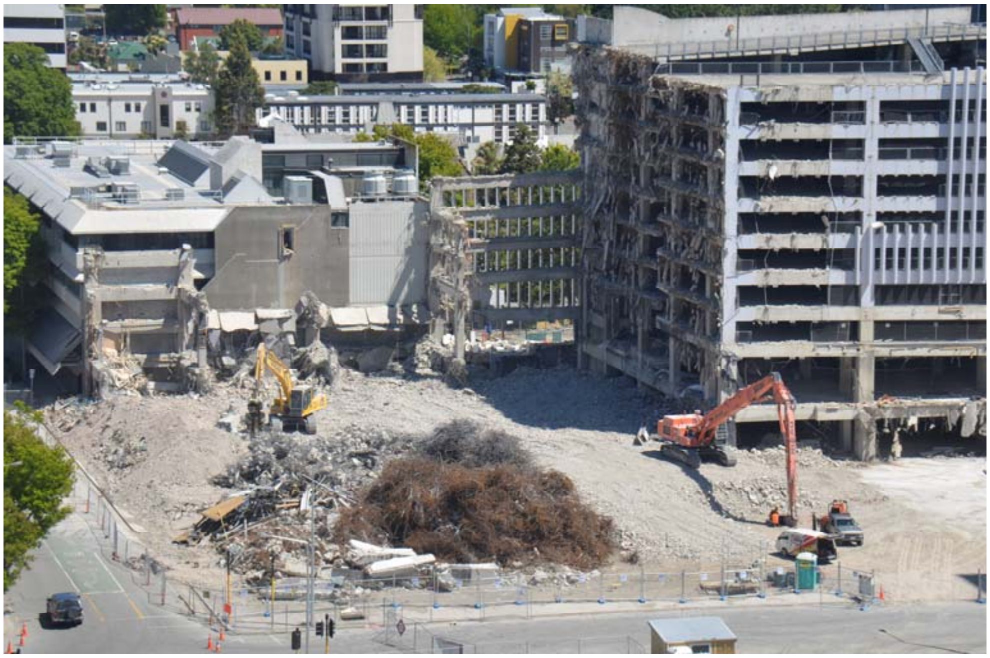

Figure 1: View of Christchurch Central Business District, November 2012. The demolished reinforced concrete has its rebar separated for recycling.

2. STEEL VERSUS CONCRETE BRACED SYSTEMS

Steel bracing, particularly the use of eccentrically braced frames (EBF) as a method of both general and seismic reinforcement is not new. There is a long history of the use of steel bracing in high rise construction dating back from the early New York skyscrapers. Buildings such as the Woolworth Building (1912) and Empire State Building (1930) made rather exclusive use of steel for their structures, including the structure and reinforcement for their cores. The larger idea behind the use of steel bracing in seismic design is the intention of absorbing the energy of the quake movement in the steel brace and permitting a controlled structural failure that permits the building to continue to stand, preventing collapse.

It is really only during the latter part of the 20th century that the use of reinforced concrete for the structure and reinforcing or bracing systems was seen to increase. Much of this can be attributed to the stylistic preferences of the Modern Movement as well as a belief in the structural capabilities of reinforced concrete. According to researcher J.P. Hollings from a paper published in 1968, around the time that many of the Christchurch buildings would have been designed,

> “Reinforced concrete, as customarily designed and detailed, and in contrast to structural steel, is essentially a brittle construction material. Brittleness can be a danger in regions prone to earthquakes. However, with due care in design and detailing, reinforced concrete structures can be made adequately ductile for good performance in earthquakes.”[1]

Hollings went on to describe various ways of designing with reinforced concrete to create the ductility required to absorb the energy from an earthquake and prevent collapse. Although this research might be considered to be “old”, there are many buildings that have been designed in zones of high seismicity in reinforced concrete that use methods that are similar to those described in Hollings’ paper. What is evident in reading this research and others is that the *primary goal* of seismic design is to prevent the complete failure or collapse of structures and prevent loss of life. The economic issues regarding ease of damage assessment, inspection, repair and eventual reuse are secondary concerns.

Although proper seismically-designed reinforced concrete structures have withstood quake events, the inspection and subsequent repair of these buildings has been time consuming and difficult. A number of innovative repair solutions have been developed, including the use of plastic reinforced fibre wraps for columns and the injection of epoxy into damaged areas to restore a percentage of the original strength of the system. [2] [3] These repair solutions must undergo quake testing to validate their potential performance in another quake situation. This type of testing is extremely difficult. In any case, the repaired reinforced concrete structure will not perform identically to the original structure. Repaired concrete also carries visual evidence of the repair. As reinforced concrete structures are often left exposed, this begins to affect the appearance of the space and potentially the confidence of the occupants. This may require the addition of new materials to cover the concrete. This will be an economic and environmental expense and make the structure more difficult to assess in the event of a future quake incident.

3. THE CASE OF PACIFIC TOWER, CHRISTCHURCH, NEW ZEALAND

Many of the larger commercial buildings that survived the Christchurch earthquake used steel as their framing and bracing system. Pacific Tower which is the tallest tower in Christchurch at 23 storeys was only completed in 2010.

> "Completed in 2010 and comprising eccentrically braced steel frames cast integrally with composite metal deck slabs, the building also incorporates several innovative features. These include carstackers, cranked braces and 'super' moment-resisting frames at ground floor level. The latter remove the need for braces from the front elevations of the building, allowing unobstructed views."[4]

Figure 2: Fracture in an Eccentrically Braced Frame in the Pacific Tower.
Courtesy of Sean Gardiner, CPG New Zealand Ltd.

The tower has completed structural repairs as of May 2013, having its steel bracing frame repaired and the hotel portion has reopened. This makes the time to repair slightly in excess of 2 years. Although a few faults were discovered in its bracing system, with only one active link showing failure, all braces had to be inspected before the building could be given permission for occupancy.

Although the steel framed building is able to be able to be reused, the need to tear out significant cover to expose the steel bracing system for damage results in significant delays to the occupancy of the building.

The steel bracing system in the Pacific Tower is concealed and is therefore taking longer to remediate. Damage must be done to the building to expose the braces for inspection purposes. This adds to the cost and time for repair. However since the inspection requires the exposure of all of the vulnerable points of the frame, the system is being retrofitted with new links as part of this process. As the bracing system was not designed with exposure in mind, many of the sections that are in need of remediation and repair are located in very difficult to access locations. This also slows the repair process.

Figure 3: A link element in a braced frame in Pacific Tower.
Note that the wall had to be torn away to provide access to the joint,
and the access is still not ideal for labour.

The focus on bracing frame in terms of reuse and adaptation does not mean to ignore the other very necessary repair work to floors, finishes and cladding that will naturally result from quake damage. But it can speed up the repair process as many of the more cosmetic repairs cannot really proceed until the building is determined to be worth salvaging and that it is economically feasible to repair.

4. INSPECTION AND REPAIR

What became very clear in terms of the examination of the aftermath of the Christchurch earthquake was the success of steel bracing to resist a quake of this magnitude. New Zealand has a very active institute that is promoting the use of steel (over other materials and systems) as a direct result of the structural outcomes of this event. The sheer magnitude of the physical damage to the Central Business District as well as to the loss of business has shifted the attention towards the economic impact in a post quake scenario. The CBD is virtually a dead zone. With such losses the business population density as decreased so significantly as to decrease the viability of those few surviving businesses to sustain themselves.

4.1. The Benefits of Exposed Steel Bracing Systems

What becomes clear is the benefit not only of the use of steel for the braced frame, but also in quake prone areas, to make the frame easy to inspect and repair in order to allow for quick and effective recovery from quake incidents. *It would be more effective to design seismic bracing systems to be exposed to view.* Engineers are not likely to object to this practice but architects normally choose to conceal such systems. This need not be the case. There are positive possibilities of exposed bracing systems, from a seismic or simple lateral bracing perspective that can be gained by taking the position of an aesthetic strategy. Exposed steel bracing systems can be illustrated to provide an effective system in allowing for reuse and adaptation in post quake situations.

Figure 4: Exposed bracing at the Lesmills Fitness Centre in Christchurch.

Exposed bracing systems have already been successfully adopted by some Christchurch businesses. The Lesmills Fitness Centre makes a simple expression of the braced steel frame behind its façade. It is architecturally exposed to the interior as well as exterior through the glazed façade. To speculate on more widespread use of this type of framing, with the added benefit of the replaceable link system seems to make a lot of sense.

Figure 5: The New Lynn Transit Station in Auckland, New Zealand uses AESS effectively to create Award Winning architecture. The diagonal braces could easily provide the basis for a “seismic aesthetic” if modified for that purpose.

Exposed bracing systems are also already part of an aesthetic of Architecturally Exposed Structural Steel (AESS) systems that can very easily be adapted to include seismic functionality and a transparency of purpose in their design intent. Exposure of these steel bracing systems can effectively create a *new seismic vernacular* that could be applied equally well to new or retrofitted structures. It is not difficult to imagine simple modifications to current AESS bracing that would make it effective as a seismic system – or vice versa.

Currently the biggest drawback to the ready adaptation of current design initiatives in AESS systems to include seismic functionality is the present fairly exclusive use of wide flange or universal sections to fabricate the braces. The use of hot rolled wide flange sections in eccentrically braced frame systems has a long history. Their use was initiated as the result of comprehensive performance testing under simulated seismic circumstances. They have had the benefit of field testing in actual seismic events, which has proven their suitability and success. The types of sections that are commonly found in AESS applications, such as round and square tubes as well as custom profiles fabricated from plate, have not been subjected to testing. That is not to say that they would not be able to pass performance tests, but only that research funding and initiatives have not included these member types.

This is a bit of a “chicken and egg” scenario. There has not been a need to validate other section types as these bracing systems are normally concealed – hence there has been no need to elevate the appearance of these seismic bracing systems to meet an architectural goal. If these systems can be seen to have merit and exposure becomes a valuable asset, then funding for testing is more likely to occur. If exposed bracing is to become a natural part of the architectural aesthetic in areas of high seismic activity, then there may be a need to initiate performance testing on alternate section types, including RHS and CHS as these are more commonly found in AESS projects.

4.2. Replaceable Link Bracing Systems

To carry this idea further, there are new systems in development that can also allow for the quick repair of seismic damage. The replaceable link bracing system has been studied in 2010 research by Nabil Mansour at the University of Toronto in his PhD thesis titled “Development of the Design of Eccentrically Braced Frames with Replaceable Shear Links”.[5] [6]

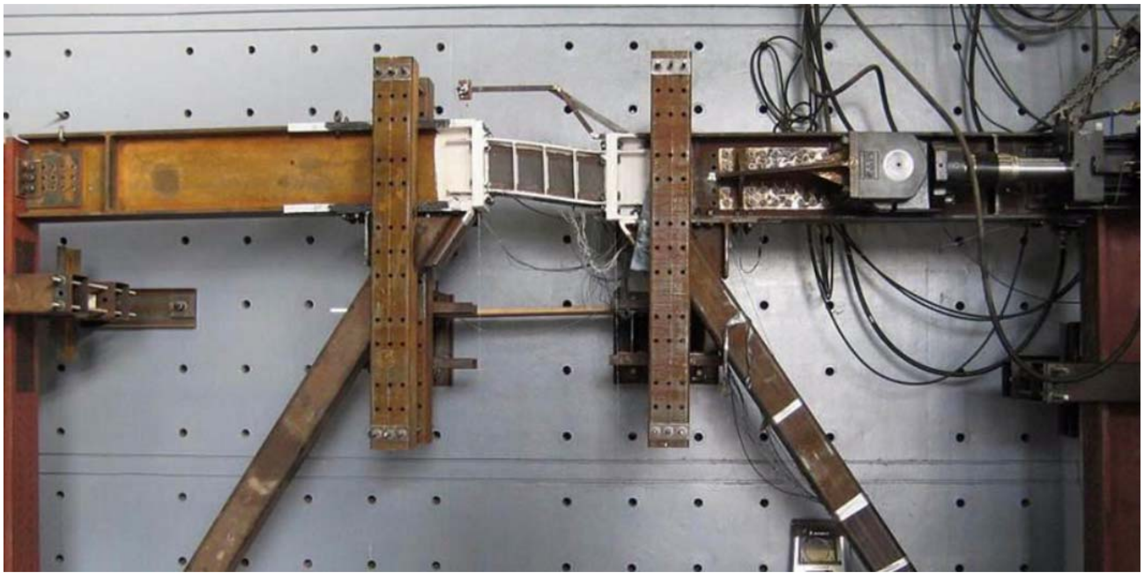

Figure 6: Test setup – frame at 1.7% drift, and total plastic link rotation of 0.113 radians.
Photo courtesy of University of Toronto.

The simple version of the idea is to create well controlled weak spots in the Eccentrically Braced Frame (EBF) that will fail during a seismic event and absorb the energy of the quake in the process. In failing the energy of the event is absorbed by the link in a sacrificial move, and the balance of the frame remains intact. If this link remains exposed, then inspection and replacement become quite straightforward. What is unique about Mansour's approach is the way that the link is bolted into the frame. Up to this point the link in EBF systems was integral to the spanning member. If the link failed, it would have to be cut out and a new section welded into place. By using a short wide flange section with plates welded to its ends that is bolted to the frame, the failed link need only be detached and a new link bolted into place (after realignment of the brace elements).

4.3. First Application of Replaceable Link Systems in the *Three35 Project*, Christchurch

What is impressive about the recovery efforts in Christchurch is the willingness to adopt new technologies to address what will be ongoing issues with seismic occurrences in buildings. Where the Canadian developed replaceable link technology has not yet been passed into the codes, it is already being applied to new construction in New Zealand. As part of this initiative Steel Construction New Zealand (SCNZ) is not only promoting the adoption of exposed steel bracing systems, but also the rapid adoption of this very new type of system with a replaceable link. With so much construction and reconstruction ongoing, it was deemed critical to take the opportunity to work towards a more effective seismic solution.

SCNZ outlined the following rationale to promote the use of replaceable link steel braces in the design of buildings in a high seismic zone.

- Proven track record of existing EBF's in Christchurch and perceived performance of steel as a "better" performer compared to concrete.
- Improved insurance and bank finance approval for a system which is easier to repair.
- Potential marketing opportunities for tenants by utilizing new seismic technology in current climate.
- Reduced downtime associated with repairs following large seismic events.
- Bolted detailing offering ease of constructability and time of erection. Also, large demand for office space in post-earthquake Christchurch due to diminished building stock means erection time is critical for optimizing rents and capitalizing on demand. Longer lead-time for concrete means steel offered faster erection times.
- Steel construction meant lower overall mass of structure and slightly decreased seismic load.

All of this would point to a system that promotes architecture that is more responsive to a quake scenario by being more adaptive if damaged.

Figure 7: A braced frame in the Three35 Project that uses a "replaceable link" in post earthquake construction in Christchurch.

The system has been used in the recently constructed *Three35 Project* in Christchurch, designed by Jasmax Architects. SCNZ in conjunction with HERA and Associate professor Charles

Clifton from the University of Auckland are currently updating HERA (Heavy Engineering Research Association) report R4-76 Seismic Design of Steel Structures (Feeney and Clifton, 1995) to include replaceable-links, partially based on experience with this project.[7]

While the design of the link is quite specific in terms of its load carrying capacity and failure mode, the design of the frames themselves can be developed to become more integral to the architectural aesthetic of the project.

5. POTENTIAL FOR EXPOSED BRACING ON RETROFIT PROJECTS

Retrofitting existing buildings to bring them to seismic code compliance is a challenge to designers. The bracing systems often end up being exposed as a degree of the difficulty of the nature of making them fit with the existing structure. If an aesthetic of exposed seismic bracing is adopted into use in general, then it will be easier for retrofitted buildings to begin to work within this framework. This would be the case in particular for situations where the bracing is placed on the exterior of the building. This form of retrofit is less disruptive to the function of the business or use, but tends to result in a disruptive aesthetic result. If exterior braces were developed “architecturally” there could be more coherence in the design, and where such retrofits are widespread, consistency in approach in neighbourhoods.

Figure 8: Existing seismic retrofit in Wellington, New Zealand.

Where possible exposed steel brace systems could be used in the interiors of buildings in an architecturally coherent manner. Again this is likely to require interest and cooperation to conduct research on the requirements for a larger variety of steel sections in order to make the systems appear less intrusive and more sympathetic to existing architectures.

Figure 9: This retrofit bracing is located in the atrium of the School of Architecture in Wellington, New Zealand. These innovative braces are using fairly standard, tested, section types but creating a different sort of bolted link section. They have become a key aspect of the architectural aesthetic of the space.

6. BRACING AS AN ARCHITECTURAL “STYLE”

The High Tech Movement of the 1970s and the current use of Architecturally Exposed Structural Steel in buildings have clearly set the stage for the creation of a vital language of exposed steel seismic bracing systems. Expressed diagonal structural systems, also known as “diagrids”, are gaining popularity in use around the world. These systems are using the aesthetic of diagonal steel bracing to create their architectural statement. This again shows the ability of expressed bracing to be used effectively in the architecture. This method of structuring a building is quite purposeful in its shift of the lateral load resistance from the traditional core and concealed bracing systems, out to the perimeter. Low to mid-rise diagrid structures can be designed in such a way that all of the lateral and gravity loads are able to be resisted by the perimeter diagrid and do not need a traditional core.

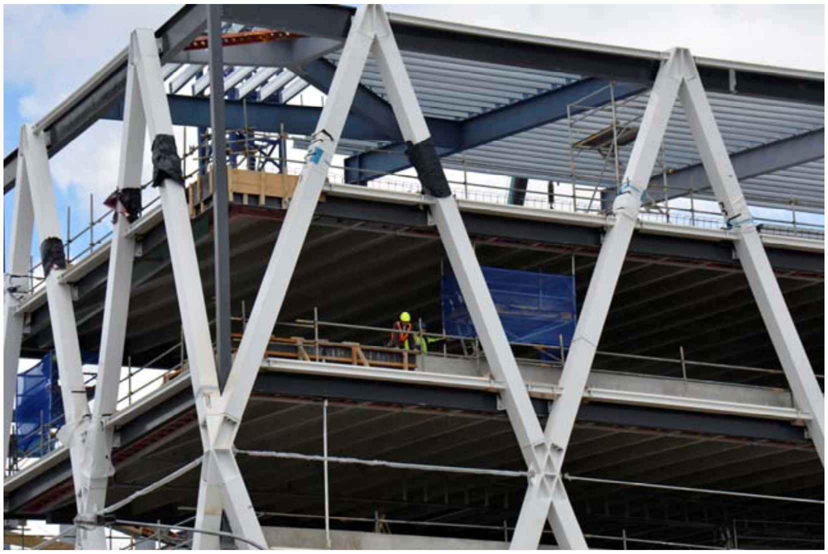

Figure 10: The Manukau Institute of Technology in Auckland, New Zealand designed by Warren and Mahoney Architects uses a perimeter diagrid on its exterior to purposefully express the structure. Note the absence of vertical columns. EBFs are used on the building interior to assist with seismic resistance. These are left exposed.

AESS bracing systems and diagrids indicate that there is potential for shifting the traditional concealment of seismic bracing systems to an exposed condition. This provides an architectural opportunity in terms of the aesthetic expression of the steel systems as well as a way to provide for quick inspection and repair in the post quake scenario. Exposure of the systems eliminates much of the required removal of finishes in order to carry out the inspections, saving time and money.

Figure 11: A system of exterior bracing is used on this laboratory building at the University of Waterloo in Canada, designed by KPMB Architects.

Figure 12: An external bracing system is used on the NEO Bankside housing project in London, England by Rogers Stirk Harbour and Partners. Although not designed for seismic resistance, the bracing system is proudly exposed and a critical part of the aesthetic of the building.

If we begin to look at the many technological developments in sustainable building systems, including the use of solar shading devices and photovoltaics for example, we can begin to see that contemporary design has begun to treat these technical systems in an honest way, and uses them to express the way that the building is responding to its environment. Architectural design sensibilities change with time, and systems that were once considered unacceptable in time come to be considered as acceptable and even preferred. This holds promise for seismic reinforcing systems.

7. CONCLUSION

The timing is perfect to rethink our traditional concealed seismic bracing systems and begin to “embrace our braces” in order to elevate their use to a unique form of architectural expression that is also feeding into early inspection and quick, non-invasive repair in a post-quake scenario.

It has been demonstrated by the outcome of the Christchurch earthquake that steel bracing systems outperformed reinforced concrete systems. Reinforced concrete buildings were extensively considered too difficult to repair and are subsequently being demolished. This extends the time involved in recovery and diminishes the effectiveness of finances and insurance monies.

Exposed steel bracing systems have clear advantages in creating buildings that are more adaptable and easier to inspect and repair after an earthquake event. This allows for quicker economic recovery of damaged areas.

The recent research into replaceable link bracing systems has created the possibility of further shortening the time for the repair and remediation of damaged buildings.

Exposed steel bracing systems are already part of the language of Architecturally Exposed Structural Steel design. It is not difficult to imagine the development of a new seismic vernacular that builds upon this language and that uses easier to inspect and repair steel bracing systems.

More research needs to be done to test hollow and custom fabricated sections to allow for variations in the choice of member type from the standard use of hot rolled wide flange or universal sections. This area of research holds great potential for the engineering community and even more possibilities when a greater variety of easy to repair steel bracing systems can be incorporated into the language of seismic architecture.

REFERENCES

[1] Hollings, J. P. 1968. “Reinforced Concrete Seismic Design” Seismic Problems in Structural Engineering, Christchurch. p 217 – 251.

[2] Catherine E. French, WenJen Tsai, Greg Thorp. 1988. “Evaluation of Techniques to Repair Moderate Earthquake Damage” 9th World Congress on Earthquake Engineering, Tokyo. p. VII 377-382.

[3] Hamid Saadatmanesh, Mohammad R. Ehsani, Limin Jin. 1977. “Repair of Earthquake-Damaged RC Columns with FRP Wraps” ACI Structural Journal. March-April. Title no. 94-S20. p. 206-214.

[4] Pacific Tower Case Study. http://www.scnz.org/events/christchurch

[5] Mansour, Nabil. 2010. “Development of the Design of Eccentrically Braced Frames with Replaceable Shear Links”. University of Toronto.

[6] Nabil Mansour, Yunlu Shen, Constantin Christopoulos, Robert Tremblay. 2008. “Experimental Evaluation of Nonlinear Replaceable Links in Eccentrically Braced Frames and Moment Resisting Frames” 14th World Conference on Earthquake Engineering. Beijing.

[7] J. J. G Ramsay, A. Fussell, R. G. Wilkinson. 2013. “Design of Replaceable Link Eccentric Braced Frames in Post-Earthquake Christchurch” Steel Innovations Conference, Christchurch.