12 PROJECTS OVER 12 YEARS : REFLECTIONS FROM IMPLEMENTING LOW DAMAGE DESIGNS

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Abstract

Inspired by Nigel Priestley's "Myths and Fallacies" lecture series in 2005, Dunning Thornton embarked on the design of a number of alternative forms of low damage technologies in steel, concrete and timber. These involve rocking systems, concentrated energy dissipation, removable/replaceable elements and more simple damage reducing changes to conventional systems.

While many of these technologies have been bred and incubated in University research programmes, the scale of loads and the different building forms designed in practice requires careful engineering innovation to extrapolate this research safely. Collaboration between researchers and consultants provides a healthy feedback loop for the continuing evolution of these technologies. We will reflect on what we believe to be the steps required to improve and ease the implementation of the technologies.

While often the focus of research is often on the structural aspects of the primary seismic system, true low damage design also encompasses the ability of the secondary structural and non-structural elements to undergo deformation or acceleration. This will also be discussed encompassing learnings from the Christchurch, Seddon and Kaikoura earthquakes during the period.

Introduction

Dunning Thornton made a conscious decision to promote with our clients low-damage technologies based on emerging research from within New Zealand and overseas. This process placed greater demands on our engineers but we believe it has created better performing buildings and has allowed us to develop a deeper understanding of how our buildings really work in earthquakes. Diverging from conventional solutions requires a possibly surprising level of additional effort throughout all aspects of design.

The recent significant earthquakes in New Zealand (Darfield 2010, Christchurch 2011, Seddon 2013, Kaikoura 2016) have shown how much of an issue disruption is to our communities. Given that it is currently harder to design low-damage buildings, it is important that there is the right research, funding and professional sharing of the knowledge required to do this.

In this paper we will attempt to summarise 12 of the buildings we have designed in the last 12 years that may be considered to have "low-damage technologies". The complexities and difficulties encountered during their design are discussed at a high level to help inform other designers of the pitfalls and suggest where future research may be targeted.

Shed 13, Wellington Waterfront. Shed 13 is a 1-storey Victorian brick warehouse with thick unreinforced masonry perimeter walls and a timber truss roof. Seismic resilience comes from a combination of post-tensioned rocking brick walls and new steel yielding elements for energy dissipation. The perimeter walls require post-tensioning to increase their face load capacity. By strengthening the foundation beam and anchoring the post-tensioning beyond the base of the wall, their cantilever rocking capacity was significantly increased to provide 50% of the seismic resistance. The other 50% came from steel flexural plates mounted atop new concrete internal frames. It was essential these frames were very stiff, and the short plates on top of the post-tensioning columns provide energy dissipation at small displacement levels.

Figure 1. Internal space of Shed 13 showing new frame and detail of ductile link to roof trusses.

Meridian, Wellington Waterfront; The Customhouse, CentrePort, Wellington. Both of these buildings utilise coupled shear walls as their primary lateral load-resisting elements, but utilise steel coupling beams to better control damage and over-strength, and to simplify buildability. Meridian is a 4-storey building with a central core and a balancing “outrigger” shear wall to control torsion. Customhouse is a 6-storey building and has a central core only. To assist with torsion control, it has additional “outrigger” shear wall panels between ground and first floor in one direction. The shear walls are coupled with U-shaped Flexural Plate (UFP) devices to tune strength and stiffness with the main core. The Customhouse was subjected to excitations at approximately its design levels in the direction shown in the diagram below during the Kaikoura sequence and a smaller proportion in the other direction. Performance was as intended for this primary system, although there was secondary damage as will be discussed later in this paper. The steel beams were replaced at a relatively low cost compared with the building’s value, and the building is now reoccupied.

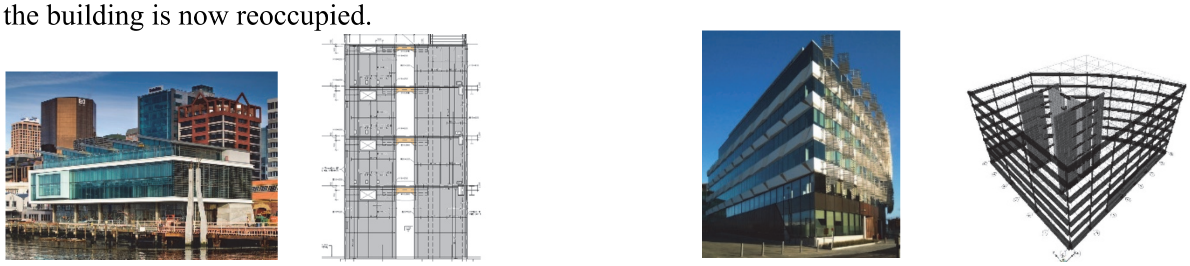


Figure 2. Exterior view and core walls of Meridian and Customhouse Buildings respectively.

Alan McDiarmid building, Victoria University, Wellington. This was New Zealand’s first PRESSS structure, with 3-bay rocking moment frames in a transverse direction and coupled shear walls in a longitudinal direction. The 5-storey building houses high-value chemistry laboratories. Energy dissipation is provided by external dissipators in the concrete frame and by steel coupling beams between the shear walls. Allowance was made in the diaphragm design for the dilation of the rocking frame through movement joints around the columns, dowel joints in the perpendicular edge beams and additional tie reinforcement parallel to the frames in the floor diaphragm. Connections to the shear walls were made using torsionally flexible, profiled composite floor.

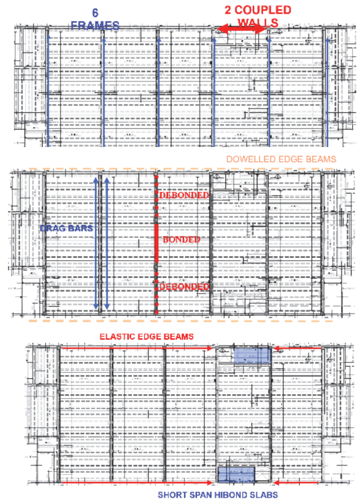
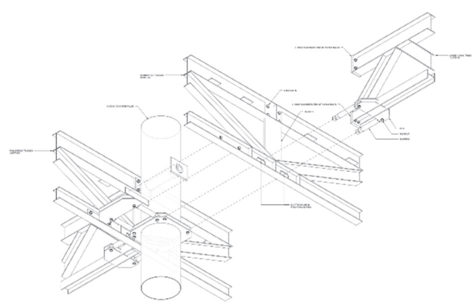


Figure 3. Exterior view. ,Plan on seismic systems, diaphragm actions transversely, and longitudinally

Te Toki a Rata, Victoria University, Wellington. With an extremely awkward site traversing a hillside, bridging a road and ending at a tightly constrained joint between two other buildings, the geometry of this building was extremely complex. The structural system employed two-way moment frames with energy dissipators between the beams and the columns. The beams were deep open trusses respecting the heavily serviced ceiling space and the columns' concrete-filled steel sections. The deep trusses allowed cantilevers in both directions past the columns to enable the complex geometries. Like Alan McDiarmid, the dissipators were steel rods necked, and confined in, grout-filled steel tubes (mini BRBs).

Figure 4. Exterior view, cross section during construction and exploded beam/column joint.



Royal Society, Wellington. This project involved the strengthening and vertical extension of a 2-storey reinforced concrete and concrete masonry building. Seismic resistance was provided by PRESSS concrete walls both in the existing building and in the new extension. The extension was used to provide the majority of the seismic resistance in the transverse direction for the existing building: it was cheaper and more practical to build in open space than in the existing building. Strong flexible connections had to be provided between the structures, however. The architectural layout of the building created several different conditions for the position and therefore the detailing of the shear walls. The walls were relatively conventional, however, with central strand post-tensioning, and energy dissipation was provided either through unbonded reinforcement at the connection to the foundation or via coupling using UFP devices.

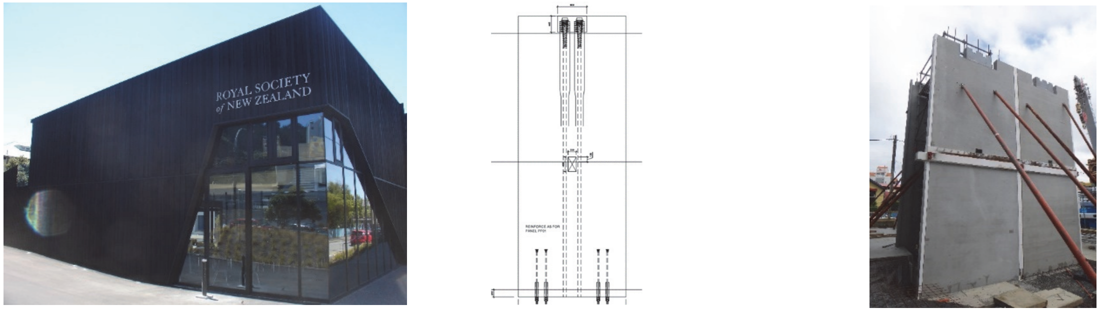


Figure 5. External view and typical rocking wall arrangement, and walls during construction.

Massey College of Creative Arts, Wellington. This is a predominantly timber-framed structure with concrete floors: the transverse timber frames are arranged to rock in the same way that a PRESSS concrete building's frames would. Due to timber's flexibility, rather than providing energy dissipation at each joint, it was provided at the building's connection to its complex concrete foundation plinth using UFP devices. Longitudinally, the building used PRESSS concrete walls arranged in a similar manner to the Royal Society building.

Figure 6. External view during construction and diagram of rocking frame and damper arrangement.

Gisborne War Memorial Theatre. Although the client provided no low-damage brief for this building, the design evolved from trying to provide sufficient damping to reduce the high seismic loads required of a Importance Level 3 (IL3) structure founded on extremely deep liquefiable silts. Seismic loads were controlled by allowing the concrete wall panels of the building to articulate, and connecting them with UFP devices. This allowed a very efficient use of the cladding panels to brace the complicated steel frame required for holding the theatre functions without imposing on the internal space.

Huddart Parker and One Market Lane, Wellington. Huddart Parker is a stiff, heavy 1920s concrete frame building: retrofit implied supplementing this with new modern concrete frames to retain compatibility. Fresh from Canterbury University's research programme and the Christchurch earthquakes, we implemented a minor change to conventional frame design using "slotted beam" technology to prevent tearing of the floor diaphragms during plastic action. This same technology was taken through to the construction of the new One Market Lane building, a 12-storey mixed use office/carpark/apartment building. The building relies on an elongated rectangular core which provides 100% of the earthquake resistance in one direction using steel coupling beams within the core walls. In the other direction the core strength is supplemented by parallel slotted-beam concrete frames though the carpark and office levels.

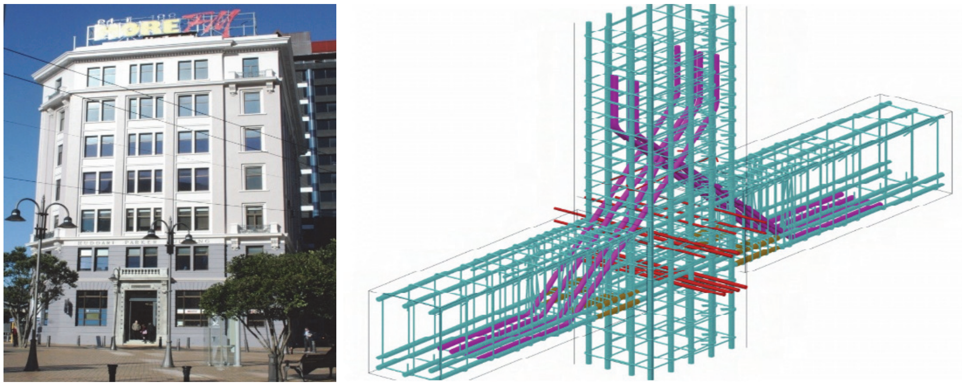


Figure 7. Exterior view of Huddart Parker, and slotted beam reinforcement arrangement.

Nelson Airport. The new airport's architecture is dominated by a sculptural timber roof form. This is braced transversely by cantilevered timber columns. Longitudinally, half the number of columns are employed as they both cantilever and have fixity to the roof above through the clerestory windows forming a large capping truss. The high IL3 seismic loads are resisted using rocking and energy dissipation from the Resilient Slip Friction Joint (RSFJ). These joints use friction on an angled surface to dissipate the energy and provide self-centring by clamping these angled surfaces together by using Belville springs.

Figure 8. Internal view during construction and detail of RSFJ.

Scion, Rotorua. A timber research organisation, this client wanted to express their field of research through their building. The 3-storey structure is braced by a perimeter timber diagrid. This diagrid is made ductile for both seismic loads and for potential geothermal/liquefaction induced ground movements by providing UFP fuses between the diamonds of the diagrid. By supporting the floors on corbels, some rocking/re-centring effect is gained in addition to the hysteretic damping from the UFPs. The rocking action is more clearly described in the diagram below.

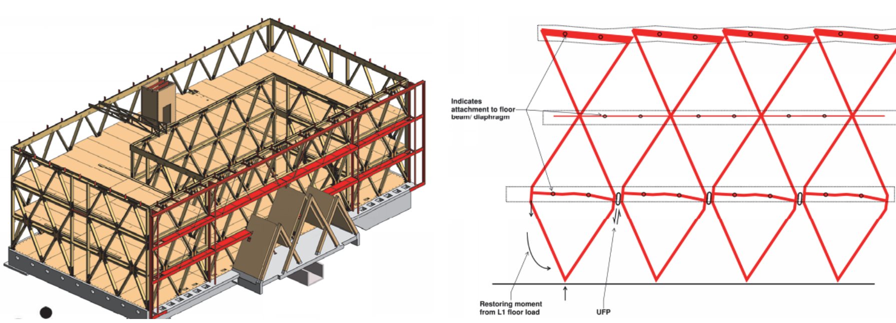


Figure 9. Render of structure and illustration of actions on ductile diagrid.

Diagrams and Communication. It is our experience that one of the key benefits of low-damage technologies is that it suggests the need to draw the building in its deformed position as a way of communicating to clients, other designers and the contractor. Rather than predicting the exact likely magnitude of these deformations, our office has developed a discipline of drawing the structure at a conservatively large displacement, to ensure the entire structure can go through these deformations. We have found that although it takes extra effort in design, it often takes little additional cost to allow for large movements in the arrangement of these connections and therefore adds significant additional resilience.

In addition, by drawing the building in its deformed shape, positions for movement joints, the bracing of services and ceilings, and the articulation of partitions and facades can be more easily understood by the other team members. To date we have had only mixed success in encouraging the design of lower-damage fit-outs, both because of industry inertia against change.

Scalability from Research. When designing the Alan MacDiarmid frame joints, we realised that by using common commercial concrete frame sizes we were going to have to resist over three times the forces at these joints than had been used in research before. It took many iterations of design to come up with the arrangement used in the building, which is shown in the diagram below.

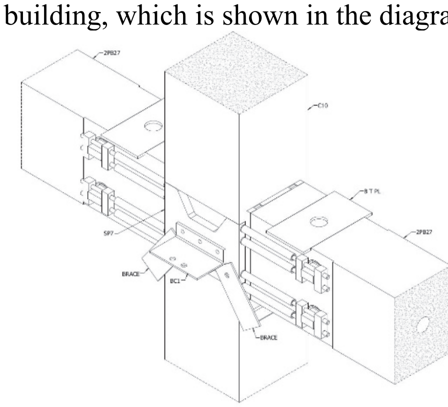


Figure 10. Isometric of beam/column joint from Alan MacDiarmid.

The result combines external beam/column reinforcement directly connected to the dissipaters, and the connection to the beam by a simple “pin” passed through a sleeved hole in the beam.

On Te Toki a Rata, the dissipators were scaled up in length to achieve greater displacements, The strain in these dissipators does not linearly scale, as we discovered during testing: strain-to-fracture is also proportionate to the diameter of the element. Single large displacements that were quickly accelerating how soon the strain to fracture would occur. Whilst there is some research in mechanical engineering on strain to fracture, significant further research is required into how it applies in the seismic field, and whether we should particularly specify how many cycles a building must go through.

The concept of unbonded buckling restrained bars was also the basis of the slotted beam technology. Intended to be simple, thorough research, however, demonstrated the importance of the arrangement of the bars at the hinging point and how they were terminated in the columns and beams beyond. When scaled up to commercial building loads in both the new and the retrofit situation, the joints became very complex and congested.

Rattle. Many of these projects involve devices which need securing to the structural elements, and consider building tolerance as well as the inherent complexities of connections which are often out of line with the primary beam and column framing. Any “rattle” in the connection lowers the amount of damping and hence its effectiveness, e.g. the pins securing the dampers in the Alan McDiarmid project. At the

College of Creative Arts seismic frames, we did not provide dissipation at the beam/column joints and instead chose stiffer, more effective positions within the structure (refer earlier section). At the Nelson Airport, any "rattle" in the devices directly causes movement of the roof: magnified by the height-to-width ratio of the column. Prototype testing showed scalability issues which were similarly magnified.

Analysis. Research naturally produces significant numerical analysis attempting to very accurately describe the predicted or tested behaviour of a new system. Many of the above systems have slowly been introduced into the mainstream with some form of "guidelines", which are often a hybrid between a textbook, a research paper and a code of practice. It is often hard for a designer at the outset to understand how much analysis and prediction is required to ensure predictable behaviour of their system.

In the author's opinion, this can lead to a disproportionate time spent on the analysis rather than on design and detailing. It is our experience that when an office tackles a new building system for the first time, before the arrangements become familiar, the design and detailing will take approximately twice the amount of time and effort than for a conventional building. As with all seismic engineering the devil is in the detail, and adequate time needs to be allowed for this. Simplified analyses such as displacement-based design should be a all that is required for many of the lower-rise or lower-complexity systems typically used in New Zealand. Defining the damping that a system provides and how the forces are correspondingly reduced by this damping adds complexity; this complexity is not necessarily adding more accuracy. There are notable differences between the change in forces from true viscous damping to those where hysteretic energy absorption provides the damping. It is also extremely important to recognise the proportion of resistance coming from rocking mechanisms (and others that don't provide significant damping) and energy absorbing systems. It is the author's opinion that the use of non-linear displacement spectra would greatly simplify analysis in a design office, using Acceleration Displacement Response Spectra (ADRS) curves for the right proportion of undamped, hysteretic damped and viscous damped force resistance.

Diaphragms and Connections. The beauty of communicating the displacement of a low-damage system is that it promotes the habit of drawing all of the aspects of a building in their displaced shape. Understanding this displaced shape and designing for these consequential actions or movements is essential if we are to create truly low-damage buildings. We have seen in the Christchurch and Kaikoura earthquakes buildings where frame dilation has caused extensive damage throughout structures. This damage is often more widely distributed and harder to repair than the damage to the frame itself.
In the Kaikoura earthquake we saw the Customhouse building subject to actions in the order of those used for design. Whilst the performance of the steel coupling beams and the shear walls themselves was as predicted, an unforeseen consequence of the displacement was discovered in the detailing of the beams. For the large shear deformations, there was a corresponding axial demand in the flanges of the beams as is shown in the diagram below. This caused secondary cracking where the beams were cast into the walls, and also some yielding of the flanges at the beam ends. Whilst this did not appear to affect the performance of the system significantly, improved detailing would require less repair.

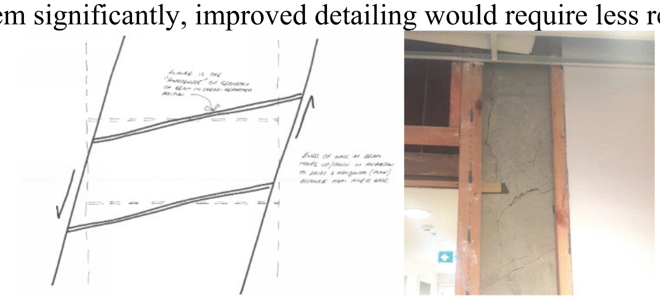


Figure 11. Diagram of elongation demands and cracking at the cast-in coupling beam ends at The Customhouse.

Connections within low-damage systems need particular care as many are designed to move during shaking. Allowing parts of the structure to move can leave elements less robust than if they were joined together using more conventional means. The shear walls in the Royal Society building were an example of this: arranged at different locations inside and at the perimeter of the building, several different forms of detail were required to provide both shear connection and to restrain the extreme ends of the walls back to the diaphragms to prevent buckling outwards under load. Providing strong connections that allow movement is difficult: if in doubt the arrangement should be physically tested.

Secondary Structures and Non-Structural Elements. Low-damage design is a balance between acceleration and displacement. More displacement reduces the accelerations within the building, but this displacement can cause consequential damage to fit-out and fittings. Less displacement increases the seismic forces, increasing the risk of poor structural foundation performance and damage to contents that are thrown around within the structure.

Ideally we could design our fit-outs to undergo the types of displacements we ensure our primary structure can withstand. However, often this is not practical: window joinery can easily slide along its length using a seismic sill, but at a corner it is almost impossible both to detail for movement and to keep the weather out on a daily basis. We believe a realistic goal is to provide good seismic detailing for the majority of a fit-out and accept damage in limited areas. Even then, following this through requires more time and energy from the structural engineer, the services engineer and the architect than would normally be expected during the design process. Typically most important decision is whether a ceiling system is rigidly braced down from the slab above (therefore shortening the length over which the remainder of the displacement is felt) or whether the fit-out should be designed as flexible so it leans over with the building's primary structure. Conventional systems in New Zealand are often a mix of the two: damage occurs where one element fights another during the movement of the building. There is a growing research and we believe this necessary as fit out damage costs can exceed structural damage costs.

Resonance. Design standards assume all buildings are excited regardless of their structural form. It is the author's opinion, based on observations from earthquakes, that some structures are less likely to be excited: they are sensitive to a narrower band of seismic wave forms. Structures that change their period with displacement (rocking structures, base isolated buildings with a high degree of non-linearity) will typically undergo fewer resonant cycles than conventional elastic or ductile structures. Surely being less likely to resonate with a set of earthquake waves is an improved form of low-damage design and warrants further research to calibrate this.

Conclusion. Low-damage technologies in New Zealand are becoming the norm rather than the exception due to the losses seen in the recent Christchurch, Seddon and Kaikoura earthquakes. We believe the range described here is only the beginning and that these techniques will continue to evolve to create new, more resilient structural forms. As this occurs, design offices need to reflect these changes back through the research and testing process. This will lead to a continual improvement in the way we seismically engineer buildings. It is important that designers give the appropriate attention to detail that is essential for these structures to perform as intended. This attention to detail is not just for the primary systems but looks for unintended consequences throughout the whole structure and preferably into the architectural and services elements as well. Simplified methodologies and the publishing of precedents will assist this. Keeping the feedback loop between designers and researchers will ensure that testing is relevant to practice. Research into the performance of non-structural systems is essential if we are going to consider holistic low-damage design. This provides a greater demand on the design engineer. Non-structural design professionals in New Zealand are interested in improving the seismic performance of their systems, which needs to be supported by our current engineers and our future research.