
Bringing Low Damage Seismic Design to Retrofit

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ABSTRACT

With the issue of the LDSG Guidelines and the first chapters of the Seismic Retrofit guidelines it is an opportune time to discuss how these processes can be brought together for retrofitting. With the Authors' experience across many LDSG structural forms and retrofit, this paper has been written with the aim of provoking discussion and awareness of the possibilities.

Retrofit is inherently limited by the form and flexibilities of the existing structure, as well as the constraints of the surrounding buildings and geotechnical conditions. These constraints will limit the LDSG ambitions, but challenge should hopefully provoke innovation, even if initiatives are limited to the new fitout elements.

Concepts discussed will include deformation compatibility (and the necessity of a deep understanding of the building's movements), the concept of repairability and the position of damage in the structure, plus ways of adapting to limit damage including selective weakening.

Reducing the damage and simplifying the post-earthquake repair of our structures in the Authors' experience does not need to be significantly costly, and any incremental improvement that can be added to our retrofits is potentially beneficial for our Clients.

1 INTRODUCTION

Existing buildings are a structural challenge as the ambitions for seismic retrofit and the Clients/Architects changes limited by the existing structure. Applying a strict framework such as the LDSG Guidelines is not only difficulty but with the inherent unknowns in an existing structure, much less certain in outcome. Instead, a structural engineer can approach a retrofit with a mindset of not only achieving resilience, but adding the additional consideration of what low damage design can be detailed in, or cost-effectively included, in the design.

This paper suggests concepts that the authors have found useful both from detailing retrofits and new buildings for LDSG. Inspiration has also been drawn from the process of assessing earthquake damaged buildings and considering repair and reinstatement.

A lower ambition approach is to put yourself into the building after a future earthquake, and think of what aspects would make this future easier for reinstating the building to as close as practical to its condition before the earthquake.

The concepts of assess ability, accessibility and replaceability are discussed, as well as overriding constraints of compatibility with the existing building but not neglecting hazards that may exist outside or below the site.

The ideas in this paper can be used auditing a Preliminary Design for possible improvements, or as inspiration to trigger improvements to detailing in the latter stages of the design process.

2 DESIGN FOR REPAIRABILITY

Design for repairability is about giving tenants, users, and occupiers confidence that they can continue to use a building after an earthquake. This applies both in the short term—immediately following the event—and in the long term, as the building remains in use.

In the short term, confidence to reoccupy can be supported by being able to assess a reasonable residual capacity for the building. “Reasonable residual capacity” will require discussion to address subjective individual concerns as well as more technical matters such as the size of the event, projected aftershocks and the scale/severity of impact if the residual capacity is exceeded.

In the long term, the author’s experience is that as near as practical to the capacity the building had before the earthquake is the level most (including insurance and finance) are comfortable with.

The technical aspects of designing for repairability are discussed below.

2.1 Structural Materials

An important aspect of structural repairability is the size and scale of the component being worked on. The distinction is between repairability and replaceability that is being made in this paper is: replaceability involves removing a component from the building and installing a new one, and repairability refers to fixing part of a component or performing a repair process in place, without full removal from the building.

This paper does not intent to cover the energy absorption characteristics and capacity deterioration of typical primary structure materials in detail. For structural steel, residual capacity relates to the level of strain and the number of cycles a yielding region in a member goes through and is reasonably well understood. However, once steel becomes cast into concrete as reinforcing the spread of strain is far more complex related to the crack pattern. Similarly yielding fasteners such as in timber structures have local strain concentrations very dependent on the relative stiffness/grain direction for the members in the joint.

Some repairability/replaceability concepts worth considering are:

- Steel damage through buckling (member or local) requires replacement rather than repair
- Concrete residual capacity is all about bond which concentrates strain near to cracks. Round bars do cause fewer larger cracks but the steel strain through debonding is less.
- Concrete structures under cyclic loading can dislodge large pieces of unreinforced material where covers are large or in lightly loaded members, which can create a severely negative perception of building performance
- Reinstating durability after concrete is cracked can have a significant effect on scope of repair (therefore disruption and cost)
- Unreinforced masonry, if damage is through rocking, is remarkably repairable (even including small areas of dislodgement/toe crushing)
- Lightweight timber/light gauge steel structures are often repaired by adding more sheathing fixings but this can destroy a ductile structural mechanism. Similar issues can occur depending on how plasterboard is fixed over specific design plywood walls.

2.2 Structural Form

The flexibility (or more often rigidity) of a structure is a fundamental part of understanding existing buildings and how to retrofit them. Lateral displacement/drift compatibility is discussed later in this section, however there are secondary effects which are less often considered during structural design. These can not only cause damage to the primary structure, but to secondary and non-structural elements.

Beam elongation of concrete frames is well documented in modern construction but also occurs in older buildings. Although the tying effect of insitu slabs, and the loss of local bond in round bars can mitigate the elongation effect, any frame elongation is effectively unrepairable. Gravity frames can elongate just like seismic frames if the columns are stronger than the beams, which is often the case in the lower levels of taller buildings. Frame elongation is not limited to reinforced concrete: older steel moment frames with “clip angle” flange connections where the clip angle yields (in a ductile manner) also elongate in most cases. This suggests low damage ambitions best limited to the onset of this elongation.

The flexibility of existing frames can be both a burden and a benefit. The higher racking displacements require more attention to the detailing/modification secondary and non-structural elements. However, a flexible frame makes it easier to add additional capacity in a stiff, ductile way that can mean the yielding of the existing frame does not occur until higher levels of shaking.

Walls are generally stiffer, but the gains in reducing damage to secondary or non-structural elements can be lost in damage due to the higher induced accelerations, or damage to longer walls as they yield and redistribute to more flexible walls.

Inherent in the behaviour of slender or tall walls is the vertical displacements induced in floors by the flexural actions. While it is easy to think of rocking walls lifting slabs and causing damage, all flexural walls exhibit the same behaviour. This is even more pronounced in coupled walls, where the compression shortening of one wall is just a coupling beam away from the adjacent lifting tension flange of the other wall. Similar actions exist in steel eccentrically braced frames over the active link, although these are somewhat less due to the flexibility of the braces. Vertical movements should be assessed, and if possible detailed in to finishes adjacent to these elements. Slabs can be made more flexible, for example ribbed composite slabs running perpendicular to the walls. EBF's in existing buildings can be detailed where the links and collector beams are isolated from floors to reduce consequential damage.

Steel concentric braced frames act in a similar way to walls: depending on the slenderness they may exhibit high vertical actions on slabs, where squat frames deflection is more in shear. Tension-only cross bracing is a special case: not only does the typically small cross-bracing allow high deflections, if it yields, the extreme pinched hysteresis this causes magnifies displacements significantly, unlikely to be useful when considering low damage design.

Part of retrofit may consider de-stiffening of the structure. Walls can be cut into similar length panels to more evenly distribute resistance across a structure. Stiff primary moment frames can be de-stiffened to allow less stiff/more economic supplemental bracing to be added. Existing “gravity” frames can be de-stiffened to reduce damage as they go through the structural displacements the primary lateral load resisting system dictates.

It is important to reduce the need to repair the structural elements that carry significant gravity loads of the building as repair or replacement is made more difficult by needing to continue to support the structure above.

2.3 Assess-ability

When designing a building, put yourself in the position of the person who is assessing it after an earthquake. How will they tell what has happened and assess the residual capacity?

Most simple systems can be assessed visually, such as plasterboard bracing where the fixings' effects on the board can be immediately seen. However, few higher-capacity bracing elements permanently show their behaviour.

The next best indication is where the displacement the structural element has been through is monitored: intentionally, such as a "scratch plate" as part of a base isolation system or unintentionally, for example a damaged partition showing the peak lateral displacement of the floor above.

While the peak displacement may give a general indication of the plastic strains a structure has been through, insitu testing may be required to give greater confidence or accuracy. Charpy testing of structural steel or Leeb testing of structural or reinforcing steel may be done insitu. To get more accuracy small coupons may need removed from the structure for more accurate Rockwell lab testing without in most cases diminishing the overall strength significantly. Measuring cracks in concrete is only a record of the residual displacements in the building and only has a loose correlation with peak displacement.

Larger components such as buckling restrained braces (BRB's) may need removal and destructive testing to assess residual capacity, especially if the building's movements were not evident/recorded. The removal of a component must be done considering the loss of residual capacity for the remaining structure.

Unfortunately, our science of predicting residual capacity of yielded steel and concrete components is not a well-defined science especially in older less typical arrangements or reinforcement contents. Similar issues exist in light framed structures braced by sheathing, where lining removal is needed for assessment and may lead to subsequent replacement regardless. Default assumptions in structural engineering tend to be conservative. It is likely that where earthquake shaking is close to the ULS level, proving residual capacity of a structure may be difficult. Therefore, a prudent designer will give careful consideration to how yielding elements in a structure may be accessed and replaced.

2.4 Accessibility

Even if we can assess our components as above, we often make this more difficult by how we arrange them in buildings. Structure such as floor slabs may mask or encase the tops of beams, or we may hide our beam/column joints in two-way frames.

Architectural encasement should be considered carefully. Hiding yielding elements behind cheap plasterboard or suspended ceilings is unlikely pose a significant cost barrier to inspection. The plasterboard may help indicate the peak displacements. However, locations such as bathrooms with tiled waterproofed surfaces, or fire-rated enclosures pose a significantly greater obstacle. Accessing structure by having to remove part of a façade is likely to be an inherently costly and intrusive activity.

Building services would ideally be positioned well away from energy-absorbing parts of the structure to allow easy inspection, and if necessary, repair. This is particularly the case for piped services, data cable bundles or heavy electrical cables, because of the cost of relocation. Fire related services have the added dimension of disruption to the building if occupied or partly occupied.

2.5 Repairability/Replaceability

When thinking about the existing components that may be damaged, or the new elements intended to yield, there are a number of considerations that will affect the ability to repair or replace that component:

- Weight – can it be lifted by a team of people, or does it need special equipment to move? Can it be transported in the building in a lift (if present), or does it need loading in using alternate means
- Size – can it be moved through the circulation routes and in the lift (if present)
- Can a component be detailed so it can be dis-assembled and reassembled to make removal and replacement easier.
- Fit – some post-earthquake residual displacement is likely so are there means of shimming or grouting that can make non-perfect fit easier.
- How many components are expected to go ductile in a building? For a seismic system, the greater the number means that the removal/retrofit of one at a time has a lesser effect on the overall residual lateral capacity. However, the greater the number of components the greater the cost and disruption of retrofit.
- Means of installation significantly affects disruption to users. Structural processes generate different levels of heat, noise, smell and vibration for which mitigation is difficult. Can detailing make this easier?
- Disruption to confidence for the occupants – how graphic will be the damage to the component? How significant will be the drop in residual capacity of the building be?

These questions can be applied when weighing up structural systems at preliminary design, or making decisions around detailing.

3 COMPATIBILITY

Understanding the compatibility of the different parts of the building displacing together is a fundamental part of assessment, and matching this with a compatible (often stiffer and more ductile) new structure is a fundamental of retrofit.

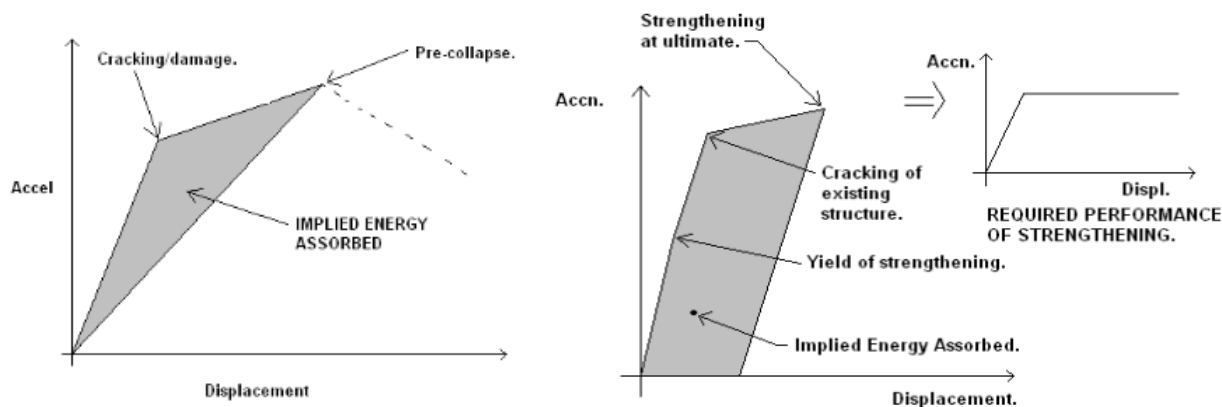


Figure 1: Copy of Figures 3 – Un-Strengthened and 4 Strengthened, from (Cattanach 2008)

Achieving good lateral displacement compatibility is the first step of achieving lower damage during earthquakes. The next is to consider modifying the existing structure to improve this compatibility.

Techniques for de-stiffening include:

- Wrapping concrete columns to improve curvature capacity and reduce spalling
- Turning long walls into shorter coupled walls to de-stiffen and add ductility
- Vertically saw cutting long brick walls into a series of panels to change the mode of resistance to rocking from sliding or diagonal tension failure
- Inserting ductile elements into rigid CBF braces
- Slotting and gravity re-supporting beams, or cutting individual reinforcing bars to remove end fixity

- Replacing concrete coupling beams with more flexible ductile elements (Cattanach 2013)
- Strength tends to be much more predictable than stiffness. Where the stiffness an existing structure has significant uncertainty, compatibility can be achieved more reliably by introduction of stiff elements of moderate strength. An example of this could be a lightly reinforced existing concrete wall building strengthened with K frames-

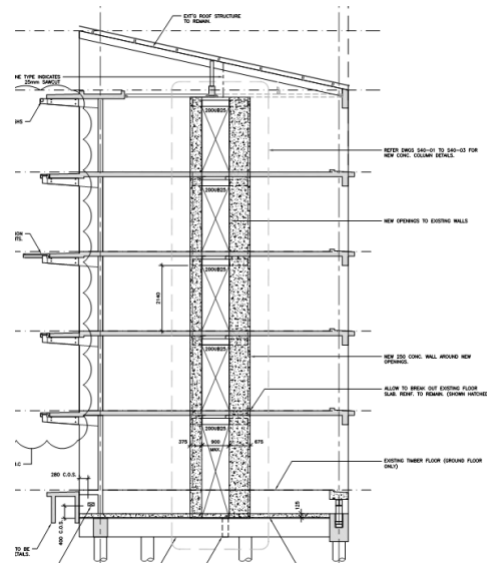
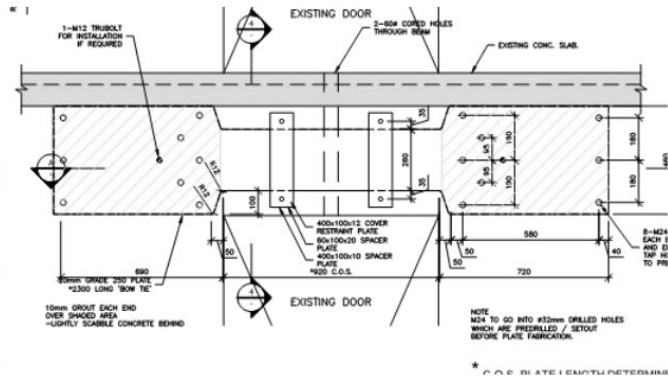


Figure 2 Newtown Park Flats, examples of de-stiffened walls and modifications to coupled walls from (Cattanach 2013)

Most importantly the movements expected in the building under different levels of shaking should be communicated to the Architect, Services Engineer and Contractor so that they can detail elements where practical/cost-effective. This information should not remain hidden in a Design Features report, but be shared with the design team in a Non-Structural Elements specification as is the practice at Dunning Thornton, or movement and tolerances report as used by some practices.

4 NEW ELEMENTS/FITOUT

The Low Damage Seismic Design guidance series, and accompanying Non-structural elements documents, contain guidance for the principles of new non-structural elements which equally applies to new elements in existing buildings.

5 SITE CONSTRAINTS

The sections above deal with how some low-damage techniques can be introduced within a building: some no/negligible cost some requiring some expenditure. However, it is important that a Client also understand if there are hazards that lie outside the building that may affect seismic performance. In some instances, mitigation of these may be warranted. In others the degree of investment in anything more than bare minimum retrofit of the building may be uneconomic as the benefits may be outweighed by the risk of this external hazard.

Hazards that should be considered include:

- Geotechnical hazards under the building (liquefaction)
- Geotechnical hazards from beyond the site (landslide, rockfall, inundation)
- Adjacent buildings which may fall/shed facades into site
- Durability hazard (e.g. high salt exposure) limiting potential useful life

6 CONCLUSIONS

Low Damage Seismic Design can be brought to retrofit projects if it is done in a “best endeavours” approach rather than the ratings set by Volume 3 of the LDSG Guidelines. This paper discusses concepts that will hopefully inspire designers to include more resilient detailing to their projects without necessarily having to significantly increase the cost of the structure. It is important to acknowledge the greater unpredictability in dealing with existing buildings but not let that constraint suppress a drive for better design wherever appropriate.

Central to the philosophy in this paper is Design for Repairability. By putting yourself in the position of an engineer retrofitting a building after an earthquake, changes can be made to the structural form or detailing to make that “future” task easier.

The authors suggest concepts included here are best applied at two stages in a project: as an “audit” at Preliminary design to see where improvements can be made in the primary concepts, and later as inspiration during the detailing phase. The intent is that low/no cost changes to structural form and detailing without complex assessment procedures can significantly improve the likelihood that a building is repaired and reused after an earthquake.

Conference Papers:

Cattanach AG, Alley GW, Thornton AW (2008). “Appropriateness of seismic strengthening interventions in heritage buildings: a framework for appraisal”. *NZSEE Conference*, April 2008, Taupo, <https://www.nzsee.org.nz/db/2008/Paper30.pdf>

Cattanach AG, Palmer S (2013). “Seismic upgrade of Wellington City Council’s Newtown Park flats”. *NZSEE Conference*, April 2013, Wellington, https://db.nzsee.org.nz/2013/Paper_4.pdf