NZS 1170.5 reimagined: From a structural designer's viewpoint

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ABSTRACT

Our loadings code has adapted and extended to incorporate new knowledge as it has emerged over the last 50+ years: could a re-write encourage engineers to design better buildings? This paper outlines some intentionally provocative suggestions from a structural designers' point of view, with the intention of promoting discussions which may assist future code committees.

Basic changes suggested involve entraining Displacement Based Design and having all of the adjustment factors turning hazard to design forces (Sp and the like) in one place and explicit. This also allows updating the scaling of time history records to more clearly benchmark against the target spectra.

Suggested simplifications for everyday use include: having non-linear design spectra (to save scaling for ductility/damping for different types of systems) and providing two-speed (simplified-conservative, or more detailed) approaches to Parts and P-Delta effects. Space should be made for some incremental inclusion of the rapidly evolving field of subsoil classification and still encourage designers to create buildings that are less prone to resonate with the ground.

A great legacy from the Canterbury Earthquakes would be a code which dovetails in with current and future assessment and low -damage design guidelines and is flexible enough to apply to the incorporation of new technologies as they emerge.

1 INTRODUCTION

New Zealand's current Loadings Code, NZS1170.5, is effectively over 30 years old. It is an adaption of the 1992 Loadings Code, which was basically the 1984 Loadings Code converted to limit state design. However, rather than designing the types of buildings described under NZS1170.5, a modern engineer more often spends their time either fixing these buildings conceived in the 1970s and 1980s or designing new low-damage design structures that can fulfil society's expectations in a more repairable way than the types of structures we saw fail in the Christchurch earthquakes.

This paper takes an intentionally broad approach to topics of design, suggesting that rather than tinkering with details in the loadings code, a fundamental restructuring is needed to help engineers approach their buildings' design in a better way. The ideal result would be a code that promotes "well-conditioned" structures that are robust against overload, that are well tied, and where all elements work in a compatible manner. The rewritten code should ideally also accommodate continued evolution in the science of engineering and seismology, allowing incremental change so that in 20 years' time we don't find ourselves in a similar situation, with an outdated approach. Such a code would be a great legacy from the Christchurch earthquakes.

2 DISPLACEMENT-BASED DESIGN

Displacement-based design was conceived of over 20 years ago, and it is mature within offshore codes and New Zealand's assessment guidelines and practice for at least 10 years, yet it is not addressed in NZS1170.5. This design process fundamentally assists engineers in thinking how a building deforms in an earthquake, and makes more explicit the calculation of energy absorption within the structure. It is also more adaptable to different forms of structure (e.g. rocking structures).

Displacement is what causes damage within structures and to non-structural elements, and in the author's opinion it should be the primary consideration of a good structural earthquake engineer. The practice of picturing the building leaning over at its Ultimate Limit State displacement (or beyond) and thinking about compatibility, stability and deformation of energy absorption elements, is effectively a mental picture (or even better a structural cartoon) that characterises a structure. Every good Design Features Report would ideally illustrate this.

As we research and test structures more, we understand that energy absorption or damping within a structure is more complex than the assumptions made in the 1970s and 1980s around ductility. To "adopt a ductility" (Grant 2016) is a practice that has been shown to easily introduce errors within structural design, and traditional (high) ductilities for some structural forms are unable to be realised when explicitly considering displacement limits or plastic rotations. Instead, damping is a combination of hysteretic and viscous models of energy absorption. In addition, the degree to which a structure continues to be elastic beyond its initial yield is not acknowledged in the traditional ductility procedures outlined in New Zealand's current loadings code.

The amount a designer chooses to absorb earthquake energy in their building must be explicitly declared and then justified by calculation. Similarly, the designer should acknowledge additional viscous damping that attempts to deal with other background phenomena. These can then be brought together to illustrate a design on an Acceleration Displacement Response Spectrum (ADRS) plot.

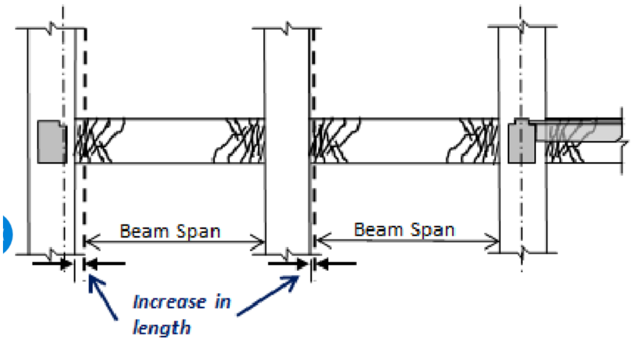
Current scaling of 5% ADRS plots is complex depending on structure type, and the scaling process is unnecessarily fraught in the author's opinion. Engineers have historically used design tables comfortably: if the NZS1170.5 included non-linear spectra plots for different levels of hysteretic and viscous damping, this would simplify the derivation of base shear acceleration.

The hope is that it would also force the justification of assumed energy absorption through calculations, a healthier and more robust approach than the assumption that ductility simply exists in certain types of structures, as can happen with ductility-based scaling.

3 COMPONENT-BASED DESIGN

The assumption that certain forms of structure have inherent ductility can easily be wrong. It is the author's opinion that the best design approach is to characterise a total building into energy absorbing elements and elastically (including overstrength) responding elements, all of which need to go through displacements as identified in the section above. This is traditionally done with capacity design and is typically adhered to with simple regular structural systems. However, textbook examples rarely exist in the real world: where the structural systems are not simple or regular and it is harder to get things right: component-based characterisation of the intended mechanism can facilitate the same capacity design goals.

Our energy absorbing mechanisms are typically more complicated than we first think they are. Concrete plastic hinges elongate differently under different levels of axial restraint. Steel active links have very different performance in flexural and shear modes. High displacement demands can cause unexpected local forces or deformations. Strain-to-fracture and low cycle fatigue are still not fully understood. Some examples are shown below.



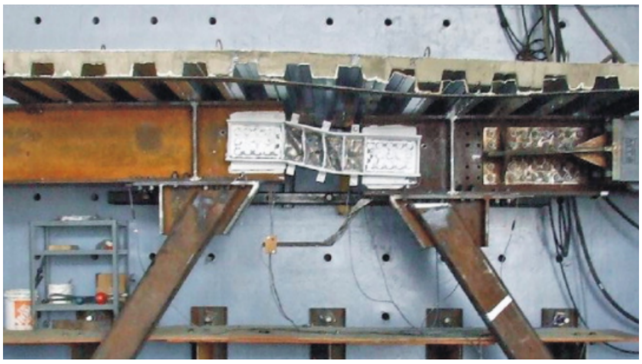


Figure 1: Common additional effects not always taken into account in design: (historically) beam elongation, Slab damage in Eccentrically braced frames

We are also benefiting from the invention of new ways of absorbing energy: UFPs, many forms of friction devices, shape memory alloys, and more affordable smaller viscous dampers all provide great possibilities for linking elastically responding components together in our structures. However, understanding the performance of these components under testing rather than just by calculation is essential, as regularly we are finding unforeseen phenomena which can significantly change performance characteristics. Some of these are illustrated below.

Figure 2: Additional effects found in energy-absorbing devices discovered in recent Dunning Thornton projects: Premature UFP failure from being cut across the steel sheet, early strain to failure of longer mini-BRB's.

Procedurally, the concept that every elastic component will be "leaning over" in the structural cartoon of the building enables overstrength forces and required rotations to be appropriately visualised and detailed (the designer's choice: detailed for (hinge) or detailed out (pin)).

4 WELL-CONDITIONED STRUCTURES

It is the author's suggestion that good design is promoted by taking well-conditioned structures to be the default and by penalising those that aren't well conditioned both with the requirement that they be able to withstand greater forces and with more complex justification procedures.

Structures that are well conditioned to resist P-delta effects either have small deformations or sufficiently high post-elastic stiffness. Elasto-plastic structures from which the current Loadings Code procedures are derived (NZS1720.5C Reference 5 dating from 1992) have poor self-centring capacity and are more prone to ratcheting. The current NZS1170.5 procedures limit effective ductility to try and control these unpredictable phenomena. Post-elastic stiffness, which can wholly offset P-delta effects, is not acknowledged and is significant for countering P-delta effects.

Torsion is instinctively a bad response in structures, yet the validity of our current procedures is not always borne out in evidence. Naturally asymmetric structures can have unpredictably (or predictably) high displacement or ductility demands, as shown in the diagram below.

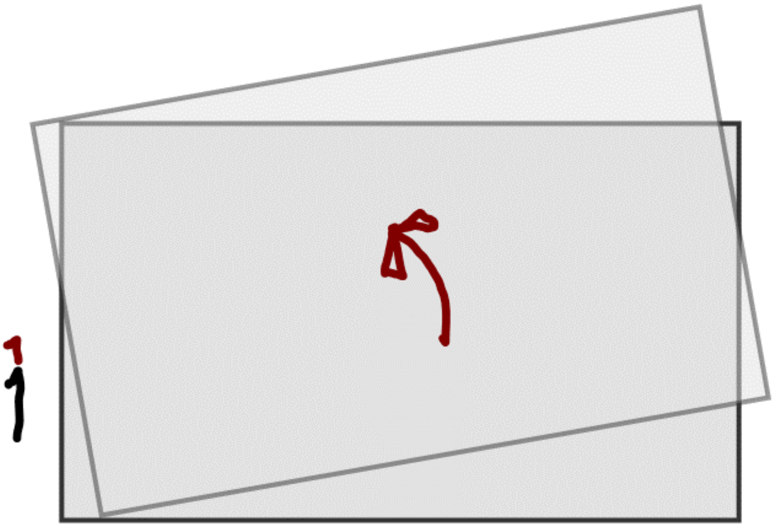


Figure 3: Demands resulting from torsion

When energy absorption is occurring at the same time, torsional ratcheting is possible. It is the author's opinion that we should either require these types of structures to be analysed in detail in non-linear analysis, or avoid designing them altogether. Torsional ratcheting in structures that are ductile in both directions should be subject to further research and benchmarking. The response depends not just on torsional stability but also on the post-elastic stiffness in both directions.

NZS1170.5's Amendment 1 attempted to address the issue of ratcheting (other than torsional). Simpler formulations acknowledging post-elastic stiffness could provide better results, in the author's opinion. However, ultimately all structural designers should be discouraged from taking gravity load paths through energy absorbing structures as this inherently causes ratcheting.

5 SIMPLIFIED LOAD PATTERNS

It is the author's opinion that simplified static lateral load patterns are the best way to create preliminary designs, to perform design checks/peer reviews, and to complete the designs of more simple structures. In the author's experience, design errors are often entrained by attempts to get more accurate load patterns: the designer gets lost in the maths. Modal analyses are somewhat outdated for all but elastic structures, but visualising the modes is an excellent way to understand the shape of deformations and the proportion of the mass that is participating in first, second or even third order mode shapes. Again, this helps in creating the "structural cartoon". It also provides a sense-check on how much loads should actually be reduced through using NLTHA (raising the question whether there should be explicit limits on this).

As the engineer "forces" the building over into the deformation shape they desire, two things happen. Firstly all elements of the building move to this displacement, whether primary, secondary or non-structural elements. Though we are decades beyond the concept of a seismic structure separate from a gravity structure, a lack of understanding of displacement compatibility continues to raise its head within engineering practice in New Zealand. Secondly, the need arises for forces to pull all these elements along together. The "tying" in the structure is not wholly/explicitly dealt with in the still relatively simple diaphragm section of NZS1170.5 and 5% of the axial load in a column. However, to engineers (and in the author's experience, to builders especially) the concept of robustness is all about these tying actions, including in foundations. Superstructure actions are more explicitly covered in UK/European code requirements around disproportionate collapse.

Irregularity makes simplified load patterns less accurate. NZS1170.5 attempts to limit irregularity to sufficiently low levels that simplified load patterns would still apply. However, without complex analysis it is difficult to predict the behaviour of "big parts" (say 10-30% of the mass) that resonate on or beside the primary structure. The author suggests this is an area for future research, and it would be helpful if the code provided more simplified load patterns that acknowledged some common forms of irregularity.

6 LEVEL OF LOAD RESISTANCE

The seismic hazard for an area does not necessarily need to correlate directly with the resistance of structures: consequence must be considered. Seismology should continue to evolve and better describe ground-shaking hazards as they develop. However, it is important that we consider the level of resistance of our structures in context with society's priorities: there has already been a significant commitment in New Zealand to seismic strengthening, and whether this should continue to increase is a philosophical question outside the scope of this paper. However, some of the consequence-based suggestions would be easily incorporated in a revised NZS1170.5; for example an increase (doubling) of the level of SLS such as suggested by (Moore 2018) may be considered a priority in our urban areas, but potentially less so in provincial or rural areas.

New Zealand has been adjusting its level of hazard with the Sp factor during the evolution of NZS1170.5 and its predecessor(s). This has been made more confusing by the inclusion of a resiliency loading that discriminates against less ductile structures, and different treatments in the material codes.

The author suggests a rationalisation of all scaling of earthquake hazard into one chapter of NZS1170.5, and making each step explicit. We could choose to design for half the theoretical hazard if the consequences were considered proportionate.

A move towards considering three conditions of structures - brittle, nominally ductile and ductile - as floated in the draft AS/NZS 1720.1 (the draft Timber Standard), is actually very adaptable to our traditional materials codes. The additional resilience for brittle structures equally ties in with guidance around high consequence failures in stairs and in transfer structures.

Additional information regarding hazard is required in New Zealand's loadings code. The number of earthquake cycles and/or the combinations of magnitude and duration, has a significant effect on the assessment of energy dissipating devices, including plastic hinges and traditional steel and reinforced concrete. Currently this information is notably absent from our code as was evidenced by the legal wrangling that followed the Canterbury series of earthquakes. In addition to this, a framework regarding resistance to immediate aftershocks would be useful in assessing resilience of energy-dissipating devices, and for assessment both of soil-structure interaction and of foundations after the full onset of liquefaction.

7 INTERACTION WITH THE GROUND

Evolutions in computing have allowed site hazard to be assessed by commercial consultancies outside of the traditional research institutions, and this remains without guidance in AS/NZS1170.5. Whilst this may give a more accurate assessment of the types and magnitude of earthquakes experienced at a site, there appear to be two fundamental gaps in converting that knowledge into better structural design.

Firstly, our understanding of three-dimensional subsoil effects appears to be significantly lacking in the ability to "codify" location-specific subsoil augmentation. Initial suggestions for amending NZS1170.5 involved a broad increase in loads. It is the author's opinion that it would be better to understand more about the natural periods of vulnerability in certain sites so that structures could be more actively designed to avoid these vulnerabilities. For example, the shaking effects seen at CentrePort during the Kaikoura earthquake would be best resisted by very stiff or very long-period (tall or base-isolated) structures rather than the mid-rise structures which were damaged by the shaking.

Secondly, our methodology of scaling previous records is very much based on conventional structure types with regard to the "period of interest". The greater range of building types, including base isolation, that we look to nowadays each have very different vulnerabilities, and it is important that records selected are scaled to an appropriate level of hazard at the shaking frequencies that excite those vulnerabilities.

Near-fault effects are crudely multiplied in NZS1170.5, and it would be beneficial to clarify how these effects should be incorporated in a suite of records, in order to get consistency in the approach of New Zealand seismologists. The localised effects above fault lines with surface propagation hazards is not covered at all. It has been up to local authorities throughout New Zealand to create bylaws to try and limit buildings for something that is not described in the code.

Our understanding of cyclic ground displacement and lateral spreading has evolved significantly in the last 10 years and now is somewhat incorporated into the geotechnical modules (but again without status under the Building Code). It is the author's opinion that the underlying framework for how this should be approached should be covered by the loadings code. This includes time to establish full liquefied conditions, and prescription around the depth within the soil matrix at which earthquake forces are induced.

8 OTHER LOADINGS

8.1 Tsunami

Associated with the seismological hazard above, is New Zealand's tsunami risk. Many New Zealand local authorities have taken a lead in creating the "blue line" evacuation zones, but NZS1170.5 does not cover the correlation of tsunami risks against the risks of other earthquake hazards or how those forces should be resisted. Offshore guides (e.g. draft ASCE 7-16) describe ways of assessing loads/resistance, but the level of hazard is something we need to establish locally.

8.2 Vertical actions

Vertical actions have been increased in NZS1170.5 following the Christchurch earthquakes. Analysis of vulnerable simple structures such as cantilevers is relatively clear from this framework. However, the methodology for considering total buildings or complex vertical systems (e.g. the participating mass of a multi-storey column) remains a research activity that has few, if any, physical examples to benchmark hypothesised behaviour. The equations are very sensitive to vertical period, which is very difficult to estimate in these complex systems.

8.3 Parts

Parts loadings are now better understood as a result of the focus on seismic restraint of building services that has followed the last 10 years of earthquakes. It is the author's opinion that the parts section of NZS1170.5 remains too complex for these very simple building services structures, yet is insufficiently detailed for considering those larger parts of buildings that are nearing the 20% of building's mass cut-off point in NZS1170.5. Common "portions of buildings' which could be considered parts and which are currently poorly analysed include rooftop additions on existing buildings, flexible annexes horizontally outside the main structure, and large concrete panels in relatively light structures.

9 CONCLUSION

The Canterbury series of earthquakes over 10 years ago stirred a significant awareness of structural, geotechnical and seismological engineering in New Zealanders. Our current NZS1170.5 is the parent code of many buildings demolished in Christchurch and many in Wellington (and other regions) requiring retrofit due to our advances in knowledge. It is time to rewrite NZS1170.5 to cover the broader range of concepts now understood in building design and to help our engineers make "well-conditioned" structures. While engineering can never be a prescriptive, recipe-based profession, a more modern approach that starts with buildings' displacement and the compatibility of all elements the author believes is fundamental to us designing better structures.

REFERENCES

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