# Implementation of Low Damage Construction: What are the Challenges?

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**ABSTRACT:** Christchurch earthquake events have raised questions on the adequacy of performance-based provisions in the current national building code. At present, in the building code the performance objectives are expressed in terms of safety and health criteria that could affect building occupants. In general, under the high intensity Christchurch events, buildings performed well in terms of life-safety (with a few exceptions) and it proved that the design practices adopted for those buildings could meet the performance objectives set by the building code. However, the damage incurred in those buildings resulted in unacceptably high economic loss. It is timely and necessary to revisit the objectives towards building performance in the building code and to include provisions for reducing economic implications in addition to the current requirements.

Based on the observed performance of some buildings, a few specific issues in the current design practices that could have contributed to extensive damage have been identified and recommended for further research leading towards improved performance of structures. In particular, efforts towards innovative design/construction solutions with low-damage concepts are encouraged.

New Zealand has been one of the leading countries in developing many innovative technologies. However, such technically advanced research findings usually face challenges towards implementation. Some of the reasons include: (i) lack of policy requirements; (iii) absence of demonstrated performance of new innovations to convince stakeholders; and (iv) non-existence of design guidelines. Such barriers significantly affect implementation of low damage construction and possible strategies to overcome those issues are discussed in this paper.

## 1 INTRODUCTION

The observations from the building performance under the Christchurch earthquake events have caused mixed opinions among the society. Many buildings survived the high intensity events without collapse but suffered extensive damage that led to economic loss that was unacceptably high; and only a couple of collapsed buildings claimed a number of lives close to two hundred. This has raised concerns about the system in place including building policies and the framework within which the building industry works. On one hand the observed performance can be attributed to the severity of the earthquake which was much higher than the 'design' level event and large number of aftershocks; on the other hand, it is worthwhile to re-examine the framework to identify the obstacles and to explore new ways of improving building performance.

Except for a very few buildings (e.g. Christchurch Women's Hospital and Southern Cross Hospital) that were constructed with low-damage design solutions, majority of the stock consisted of conventional structural systems using structural walls, moment resisting frames and braces. The conventional designs use the concept of 'ductility' which means the design accepts 'damage' without compromising on life-safety. Thereby, understandably the conventional structural systems can be treated as damage prone construction (DPC). Unfortunately, economic loss due to damage and business interruption could become unacceptable to clients as evident from the Christchurch events.

Hence, the building industry should take necessary steps towards design of buildings that sustain minimal damage and ensure continued functionality.

One of the areas that appeal to the structural engineering profession is low damage construction (LDC) that aim to develop ways of reducing damage and disruption to the functionality of the building in addition to life-safety. Innovative solutions use new design approach, new devices and new construction methods to achieve the objectives. Ironically, new concepts and innovative solutions face barriers and challenges in the way of implementation. However, it is encouraging to note that a few owners/developers in Christchurch rebuild projects have come forward to choose low damage constructions with improved performance criteria for their buildings. But that does not mean that all the systems are in place within building industry that enables to facilitate low damage construction in large scale.

In this paper, building policies in place and some barriers that exist in the way of potential adoption and implementation of low damage construction within New Zealand context are presented. The points presented within this paper could collectively represent views from various speakers who presented at the Royal Commission hearings under 'New Building Technologies'.

## 2 BUILDING CODE PROVISIONS

The Building Act 1991 sets out a legislative framework for building controls in New Zealand. Regulators are responsible to the public and are empowered to represent public interest and expectations for how buildings and facilities are expected to perform. The First Schedule to the building regulations is known as the New Zealand Building Code. In accordance with the Building Act, the building code sets the objectives and goals related to functional and performance requirements of a building structure including construction, demolition and alteration work. References are made to Standards (loading standards and material standards) which describe methods to be used to demonstrate the performance outcomes of the structure.

The building code adopts performance-based approach and it specifies expected performance outcomes rather than specific solutions. The totality of the building regulatory system is captured in a performance system model (PMS). It is typically formatted as a hierarchical structure (Figure 1) in which the top level contains goals and objectives expressed as qualitative statements. Functional statements are stated to satisfy the objectives. Further, operative and performance requirements that satisfy the functional requirements are provided. Note that the above requirements are considered to be high-level and are descriptive and qualitative. Currently, the building code addresses tow criteria: 'life-safety' under rare events and 'serviceability' under frequent events as minimum requirements to address tolerable levels of safety and health concerns of occupants.

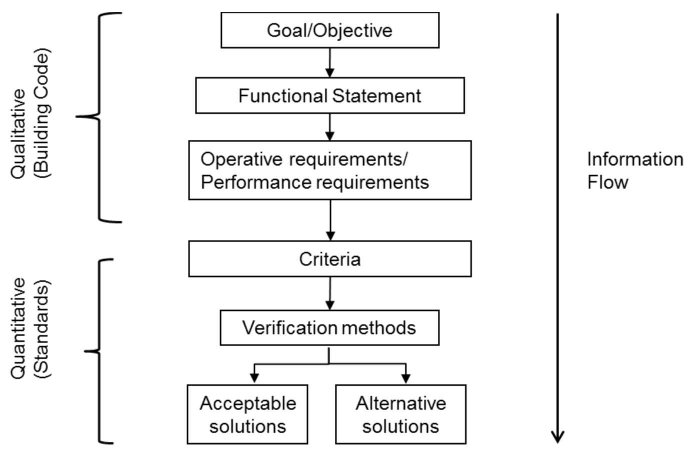


Figure 1 Performance system model (adopted based on Maechem, et al, 2002)

Following this, performance criteria satisfying the operative and performance requirements are stated within the standards. Standards provide quantitative information to enable achievement of the desired performance criteria. Acceptable solutions are usually "deemed to comply" solutions that generally include the former prescriptive solutions, i.e. the solutions that society has accepted over time as being "acceptable" or "appropriate." As the building code adopts performance-based approach, there is a provision for 'alternative solutions' which essentially allow using new design solutions and materials to achieve targeted and improved performance outcomes underpinning the performance-based design concepts. The verification methods can be in terms of test methods, analyses, and demonstrated performance.

Design standards are referred to as mandatory documents by the building code where as some supporting documents such as 'design guidelines' remain as guidance documents without being treated as mandatory. Note that the mandatory documents facilitate design approval stage better as they are referenced documents. The combination of building regulations, enforcement mechanisms, standards, guidance documents and related support measures form the building regulatory system.

The building code has not only addressed 'life-safety' and 'serviceability and functionality' as performance criteria but there are also mentions on 'amenity'. However the term 'amenity' is not discussed in detail and so the current design practices do not explicitly account for this. Work is underway to define tolerable impact (performance) levels against different hazard intensity levels within new revisions of the Building Code addressing amenity, functionality, and strength and stability requirements for life-safety. Developments in engineering design should be able to demonstrate these multiple performance levels without involving undue efforts.

Recognising the importance of continued functionality and reduced damage, new building technologies providing damage-resistant solutions could become a preference for building owners and other stakeholders. As such, some of the issues in executing these new-design solutions as part of 'alternative solutions' will be discussed.

## 3 LOW DAMAGE CONSTRUCTION

Low damage construction involves new building technologies to construct resilient and sustainable structures to mitigate earthquake risks. In principle new technologies, are devised either to reduce the demand on the structure (e.g. base isolation techniques) or to effectively control the response of the structure and non-structural components (e.g. a combination of rocking systems and damping devices). Discussion on types of LDC technologies is out of the scope of the paper; but the reader is suggested to refer to a comprehensive summary on 'New Building Technologies' including the ones invented in New Zealand reported to Royal Commission (Royal Commission Report, Vol.3). The report also discusses pros and cons of various systems.

Recommendations from Royal Commission on low-damage building technologies (Vol. 3, section 7; recommendation points: 66 to 70) are mainly directed towards: (i) continued research in the development of low-damage technologies; (ii) availability of evidence-based information on different aspects of low-damage technologies to design engineers and building consent authorities; (iii) development of reference documents for such technologies that provide convenient methods of design and verification; (iv) better communication and knowledge dissemination of new technologies among various sectors of building industry; and (v) integrated approach in building design and construction to avoid damage to secondary elements in buildings that pose life-safety hazard. A brief discussion on the current status that led to these recommendations will be included in the later section of the paper.

Past earthquake events and building performances have enabled structural engineering profession to have better understanding on damageability and reparability of structural components including cost implications. New design technologies aim to provide control over damage and also driven to yield economic benefits. Such technologies when adopted for a building, their efficiency may need to be verified. A few studies (Hare, et al., 2012, Golondrino et al. 2102) have identified specific characteristics that should be addressed by low-damage design as: (i) damage mitigation effectiveness; (ii) system reparability; (iii) self-centring ability; (iv) non-structural damage; (v) durability; and (vi) affordability. Also, a method of calculating 'sustainability index' for steel structural systems using four major damage indicators such as 'floor damage', 'drift damage', 'element replaceability', and 'permanent drift' is suggested (Golondrino et al., 2012). Recently, efforts are being taken under

‘Quake-Star’ programme (Parker, et al., 2012) to create a system where buildings are rated according to their capabilities to be resilient after an earthquake. A measure similar to ‘sustainability index’ would be helpful in rating the building. Buildings that adopt low damage construction will be given high credit due to their sustainable performance.

# 4 BARRIERS IN ADOPTING LDC

The outcome of performance-based design is affected by a number of factors which include the policies in place within building industry; robustness of design approach followed; quality of research outcomes in providing sustainable solutions; institute-industry interaction to test the solution and to provide evidence-based information; market value of design choices; and communication between the client and the engineer/architect to understand the needs and the deliverables. The gaps within the factors and missing links between the factors affect the quality of final outcome and they become barriers in achieving the outcome.

Low damage design and construction solutions are generally practised under performance-based design concepts. International Code Council Performance Code (ICC PC, 2009) defines performance-based design as “an engineering approach to design elements of a building based on agreed upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria”. When the building owner aims to have reduced loss and continued functionality for a specific hazard level, performance-based design provides a framework to tailor the design and to achieve the targets.

May (2002) investigated the likely impediments in implementation of performance-based design concepts in parallel with issues in adopting new developments such as base-isolation techniques and load and resistant factor design (LRFD) concepts. General notion on high perceived costs and lack of credibility and confidence among engineers and public in new design methods were reported to be some of the factors affecting implementation. He also included a few suggestions such as extensive expenditure of governmental funds on research and development of new technology, aggressive marketing of the technology by large construction companies, and a building approval process that undertakes the technology to address the challenges towards implementation (May, 2002).

Some prominent factors that potentially affect LDC within New Zealand context are discussed below.

## 4.1 Policy statements in Building Code

Building code regulatory requirements primarily address minimum requirements of safety and health criteria as a result of damage to buildings but not anything related to economic concerns. So, from code compliance point of view, there is no driver to minimise damage in buildings to reduce economic loss and thereby LDC will only become optional to the interest of stakeholder. Many building owners or developers of private sectors show interest to have buildings that satisfy minimum requirements to be code compliant and not many of them are aware of the fact that the building code provisions are only minimum requirements; and the buildings are susceptible to damage while being able to save lives and the economic loss could be unacceptable for them. Educating the owners of such risk could motivate them to aim for higher performance levels which are possible through LDC.

Besides, within the performance-based approach, the current descriptions in the building code related to expected performance criteria are qualitative and frequently use terms such as ‘adequate’ and ‘reasonable’. These terms are subjective and result in ambiguity. Lack of quantified measures of performance criteria could make verification of performance outcomes of a design a difficult task.

## 4.2 Demonstrable performance

It is possible for engineers to demonstrate that their design will meet the performance objectives of the building code using information from various sources to develop an “alternative solution” for LDC. Unfortunately, the effort required for such a demonstration is large, and number of practicing engineers who are both energetic and comfortable enough to pursue such a path is small. It is much easier if LDC technologies are documented well and if proper design guidelines are available as "acceptable solutions" which the engineering profession can adopt with confidence. Currently, design guidelines have not been developed for many LDC technologies. Unlike conventional structural systems, new technologies generally use external devices for energy dissipation. So, many design solutions could become building specific. Principles of design with such new devices can only be documented for reference and intrinsic detailing aspects will have to be decided by the engineer-in-charge.

For example, base-isolation technology is pioneered in New Zealand, proven with scientific credibility and has demonstrated high performance levels during earthquakes all over the world. Typical design guidelines such as the one published within New Zealand (Kelly, 2001) is not yet cited by the Building Code to be a 'reference document'. The methodology and the respective design guidelines are expected to satisfy certain criteria to be considered eligible for code citation. Referenced documents are trusted by structural engineers for design and building control authorities for approval of building.

New design solutions will need to be proven for their 'credibility' in performance outcomes to gain acceptance from the market. Marketing of any solution or product is all about creating value for the clients and striving to meet (if not exceed) their expectations. This could be addressed through extensive research, testing, addressing maintenance issues over the life-time of the building and documenting them properly. New design solutions have somewhat gained the acceptance of 'educated' stakeholders and public departments. Such buildings could set examples for other stakeholders to consider and gain confidence and with increasing trend to adopt LDC could place a requirement to the development of approved/mandatory design standards in the future.

### 4.3 **Cost factor**

Any new technology that deviates from the conventional practice brings a query on cost implications. As May (2002) indicated, the cost comparison between the new and conventional designs should be done carefully; because new technologies aim at reduced damage and continued functionality whereas conventional systems allow damage and do not guarantee continued functionality. Some publications have indicated a minimal increase in initial cost. Private building owners could well be interested only in the initial cost and would not see a long-term ownership of the facility to take advantage from life-cycle cost benefits. The cost can vary with respect to 'demand-supply' factors in the market.

### 4.4 **Peer review and building consent process**

Currently, many low damage construction adopt new technologies and they come under 'alternative solutions' and hence peer review process become a very important phase of the project. Professionals involved in peer review process are expected to be sufficiently competent to verify the design. Unfortunately, at present, lack of such professional engineers with expertise developed in new design technologies add to the difficulty of consenting process; and potentially leading to delay in approval.

### 4.5 **Construction industry momentum**

The construction industry around the world is conservative. Established norms and protocols make it difficult to adopt new technologies even if these technologies offer cheaper structures with better performance.

## 5 **WAY FORWARD TOWARDS IMPLEMENTATION OF LDC**

A number of factors play significant role in implementing LDC. The factors are so intertwined that they influence one another very strongly. There is a need to view the contributions and responsibilities of various sectors holistically and a framework that works towards successful implementation is to be developed. Some of the factors are discussed below emphasising their role in deriving the benefits of LDC.

### 5.1 **Policy level**

Building Act is the Act passed by the Parliament. New Zealand Building Code is a regulation that is made under Building Act. Policy statements within Building Act are supposedly representing accepted opinions of the public/stakeholders of building industry. After the Canterbury events, it is clear that the public express concerns over the economic implications and probably it is time for necessary changes to take place in setting the performance requirements and objectives for building design within the Building Code. As suggested by a few researchers (e.g. Priestley et al., 2007 and Hare et al. 2012) a limit state such as 'Damage control limit state' could be incorporated. Hare et al., (2012) have discussed on a possible framework for adopting LDC within New Zealand context and being in compliance with New Zealand building code requirements. The driver to make this happen is strong representation towards minimised loss from the stakeholders of building industry. Because the implications of poor building performance affect not only the building owners and occupier, it seems reasonable that the Damage Control Limit State be the default for all design. In this case design to the current ULS would be permitted only based on special submission to the responsible authority showing that effects to society of a life-safe unusable building is not undesirable.

## 5.2 **Demonstrable performance**

Any kind of change or improvements in design with new products or methodology is strongly influenced by sound technical and scientific information from research outcomes that have demonstrated quality, sustainability and reliability. This can be achieved through research advancements along with industry interaction.

### 5.2.1 *National integrated research approach*

Academics and researchers are in a stronger position to provide technically supporting information. At present, different strands of research activities are being pursued that address various elements of LDC. However, there seems to be lack of co-ordination among the research efforts that results in critical 'missing links' and thereby not addressing relevant questions that various stakeholders would like to be informed. A co-ordinated and well-structured flow of information among research projects will enable better understanding towards addressing 'missing links'. An agreed version of what the 'missing links' are is yet to be established and a project (funded by the Natural Hazards Research Platform to GNS Science in collaboration with University of Canterbury) has just begun to address this issue. Such 'completeness' will increase the market value of new innovations facilitating the uptake.

Research needs are supposedly driven by the need to serve public expectations. In New Zealand, high calibre research advancements to provide low-damage solutions are continued within research organisations including performing experimental investigations. The experimental facilities are limited in size and capacities and often scale models or components are investigated. There is a tendency to overlook the integral performance of whole structure when improvements are focussed at the component level. Some design solutions enhance the displacement (drift) capacity which can potentially benefit the structural response; on the other hand such solutions warrant better features than the ones available with existing non-structural components to accommodate increased displacements.

It is recognised that international collaboration on experimental investigation are on-going to some extent and possibilities of enhancing these avenues should be explored and encouraged to exchange research outcomes considering the limitations of experimental facilities within New Zealand.

### 5.2.2 *Institute-industry interaction*

Invention of design solutions with appropriate standards is possible with strong institute-industry interaction. Research interests from academic institutions can be well supported from contributions from industry. Institute-industry interaction could potentially play a major role in testing new products for their performance and suitability to be adopted in design and construction. It is required that compliance of new products needs to be demonstrated through testing or observed performance from past earthquakes. Sometimes, proprietary products from overseas may be adopted but after verification in the context of New Zealand conditions. Testing of products or models is to be encouraged and a framework for evaluation services can be set up in a form very similar to ICC-ES (International Code Council – Evaluation Services, USA). At this stage, it may be required to develop testing protocols and acceptance criteria for products for consistency in establishing the performance criteria set from New Zealand perspective.

In building industry, interaction between the clients, architects and engineers at design and construction become crucial for the successful completion of a project. Interaction could also include an 'education' phase where different technical players are made aware of each other's expectations and limitations.

### 5.3 Cost information

Both initial and long-term cost need to be considered. In Japan, the use of base-isolation technology produces a better performing lower initial cost building than that a conventional building. As such, the use of base-isolation is widespread. In NZ, base-isolation has been described by different consultants in terms of the initial cost as being "break-even" or even slightly more expensive. One building using friction and rocking technologies in Wellington was 0.5% more expensive than the initial cost of an equivalent conventional structure. It is possible, that with smart thinking and with an experienced construction industry in low damage technologies, that LDC will be significantly cheaper than conventional construction and significant work is being conducted in this area.

The long term cost considers savings due to the lack of damage from the new technology. While Christchurch building owners may have been reluctant to pay extra for better structures before the Christchurch earthquakes, afterwards building owners wished they had been more diligent in requiring a better design. Any extra cost requires a paradigm shift on behalf of society from ULS to LDC construction. This is possible as it has already happened in the greater paradigm shift from no seismic design to ULS design. There are many other examples of people spending more to mitigate the possibility of a significant rare event such as the use of seatbelts in vehicles, and car seats for children. Motivations for LDC from the insurance industry, or from the building resale market, may also assist in this regard. Proper cost-benefit analyses over a period of interest should be done rather than looking only at the initial cost. Reduction in insurance premium or increase in the capital value of the building could motivate the owners towards LDC. This is where public buildings have come forward to bear with cost effects at the initial and long-term basis.

### 5.4 Peer review and building consenting process

Design engineers and building consent authorities (BCA) should be informed about the new developments in low damage design and construction techniques and given educational trainings to understand and apply in their field. This could help in increasing their knowledge and skill to perform their task which can eventually facilitate building consenting process to be faster. A smooth consenting process can significantly increase the chances of adopting LDC.

### 5.5 Construction industry momentum

Changes are made by constant education at all levels of the construction industry. Case studies of successful low damage structures need to be constantly described so that industry participants can easily see that they are part of a major improvement. This is done through seminars, workshops and conferences backed up by peer-reviewed journal articles. Already, some leading edge NZ consultants/contractors have understood the potential benefits of being on the leading edge, and have implemented LDC in actual structures making it easy for others to follow. Readily available design/construction guidelines also facilitate here.

## 6 OTHER CONSIDERATIONS

### 6.1 Overseas developments in performance-based design

Under PEER (Pacific earthquake engineering research centre) framework, significant amount of research is being undertaken to facilitate application of performance-based earthquake engineering which aim to satisfy client expectations on building performance. Recent advancements include the development of assessment methodology that considers economic aspects and enable making informed decisions. For example, under the FEMA project FEMA P-58, Applied Technology Council carried out a project ATC-58 to develop "Guidelines for seismic performance assessment of buildings" in alignment with 'Next generation performance-based seismic design criteria' [FEMA 445, 2006]. The guidelines document summarises the methodology, procedures and criteria needed to predict the probable earthquake performance of individual buildings based on their unique structural, non-structural and occupancy characteristics, and the seismic hazard exposure at a given site.

The procedure suggested by ATC 58 is incorporated in the form of a software tool, namely PACT (performance assessment calculation tool) which requires basic input data including damageability (fragility) of components that comprise the building, and the consequence of damage in terms of potential casualties, direct economic loss and downtime. Currently, the software has a library of functions that may be appropriate for only US buildings. Careful interpretation would be required to use those functions for New Zealand buildings. A similar tool SLAT (seismic loss assessment tool) has been developed within New Zealand (Bradley, 2009). This tool is not as extensive in terms of fragility function as PACT and uses many fragility functions from US research database.

A sensitivity study of fragility and consequence functions of components on the assessment will give helpful information on prioritising the research needs on development of new fragility functions. It is worth mentioning that PACT provides flexibility to incorporate new and additional data and this feature gives the opportunity to use the tool for New Zealand requirements and to verify performance outcomes of LDC.

### 6.2 Stakeholders engagement

In the year 2000, FEMA 349 established action plans for implementation of performance-based earthquake engineering. One of the primary objectives was to raise awareness among stakeholders on how performance-based design can address many of the problems associated with current design practice. It appears that this step towards communicating risk and the uncertainties involved in the process in simple terms that can be understood by stakeholders, is yet to be taken in New Zealand which could benefit implementation of LDC.

On-going work to define ‘tolerable impact levels’ (TIL) in the new draft of Building Code should essentially reflect the stakeholders’ views. A preliminary study has been carried out to address the current status of performance-based approach in New Zealand and to propose measures towards establishing tolerable impact levels within the performance-based design framework (Uma, 2012). It is believed that a consortium of experts/stakeholders representing various sectors from the building industry should be formed. Only a joint effort combined with exchange of knowledge and information amongst representatives of various sectors can possibly establish limits of tolerable impact levels that are comfortably accepted by industry stakeholders.

FEMA P-58 (under which ATC 58 project was handled) is continuing to look at developing guidelines for stakeholders in making decisions as a part of performance-based design. It is believed that efforts towards collaborative investigation with FEMA project would be ideal and timely in establishing guidelines for the benefit of New Zealand stakeholders.

Insurance policies in force and risk management strategies preferred by the stakeholder could play an important role in decision making. It appears that insurance policies from many providers do not necessarily recognise the advanced designs and their benefits. Probably, demonstration on the credibility of new design solutions in reducing damage could help the situation.

### 6.3 Improving resilience in regional sense

Huge economic implications that resulted from damaged buildings within central business district (CBD) of Christchurch, suggest the need for identifying ways to improve resilience of such important/high impact region. For example, it can be made mandatory for buildings that are constructed in any important location (similar to CBD area) to be designed to achieve higher performance outcomes. Such compliance could bring uniformity in performance of buildings in that region and could alleviate the problems associated with disruption of functionality of un-damaged buildings due to other damaged buildings in the vicinity. To encourage the builders, the Government should come forward to provide incentives or some form of tangible benefits to them. However, it is important to note that the continued functionality for a building in site could be ensured only when the infrastructure around the region is able to sustain its functionality. This highlights the inter-dependency between various sectors and their inter-functionality in making a region resilient.

## 7 SUMMARY AND CONCLUSIONS

New Zealand Building Code regulations follow performance-based approach and offer freedom to adopt new innovations towards improved performance objectives. The recent lessons imparted by Christchurch earthquakes have called for our attention to design buildings for better performance levels that can control damage and reduce economic impacts. This can be achieved in buildings by adopting low damage construction technologies. In this paper, some factors that are recognised as potential barriers within the current system in adopting low damage construction practices are discussed. The decision making process on opting for low damage construction will not be always a straightforward one as much have to be learned in order to overcome the obstacles of unknown cost benefits, uncertain comparative advantage, complexity and other uncertainties.

It is recommended that integrated approach and improved communication between various sectors should be established to realise the full benefits of low damage construction.

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