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Are stronger, stiffer buildings indeed costlier? - Case study of RC frame buildings

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ABSTRACT

Reinforced concrete (RC) buildings designed as per current seismic codes/standards are expected to satisfy “life safety” in a design level earthquake, but modern buildings have suffered significant damage in recent earthquakes, which were either irreparable or required lengthy and costly repair. Seismic codes/standards allow buildings to be designed for different lateral strength as long as the associated ductility and drift demands are catered for. The design seismic force is primarily controlled by a force reduction factor; a higher reduction factor leads to weaker/softer building but requires stringent confinement detailing to achieve a higher ductility. Buildings designed for higher reduction factor are more likely to suffer structural damage in moderate earthquakes. It is intuitively believed that stronger buildings, which respond elastically in a design level earthquake, are prohibitively costlier. However, cost of building skeleton, which governs its strength, is only a minor contributor to the total project cost. This paper conducts cost analysis on RC frame buildings designed with different reduction factors to investigate their effect on the construction cost. Based on the cost breakdown, it is found that the structural material cost of low-medium rise RC frame buildings is normally 25-30% of the total project cost, which varies within ±10% for the full range of force reduction factors allowed by modern building standards. The additional initial cost required to design RC frame buildings (with ductile detailing) that respond elastically in design-level shakings is insignificant when compared against the cumulative reduction in damage repair costs and financial losses due to business interruption over their lifetime. Hence, to achieve low-damage design through traditional measures, engineers should be encouraged to design stronger and stiffer buildings so that they remain in “operational” state after a DBE.

1 INTRODUCTION

During recent major earthquakes, while modern RC buildings were generally found to have satisfied the life-safety performance they expectedly suffered extensive structural and non-structural damage (Kam et al 2010, Kam et al 2011, Dhakal 2010). Most of the damaged RC buildings were either technically irreparable or were assessed to require huge cost and significant downtime to repair. In the aftermath of these experiences, building stakeholders have become reluctant to continue with the status-quo of ductile design philosophy (which inevitably invites damage in moderate earthquakes) and shown a growing desire for alternate design approaches which ensure buildings are not only life-safe in major earthquakes, but also incur minimal (if any) damage that can be easily, quickly and cheaply repaired. This has triggered accelerated research and development of multiple low-damage building technologies (i.e. base isolation, jointed post-tensioned systems, external braces and dampers, demountable building system etc.) which aim to minimize seismic losses and downtime (Pampanin 2005, Aninthaneni and Dhakal 2017). Nevertheless, most of these technologies minimise only the damage to a building's structural systems and need to be augmented by low-damage non-structural systems as well if a truly low-damage building performance is to be achieved. In general, there is a lack of realisation that the upfront cost of buildings and their seismic losses (including downtime) are dominated by the damage to their non-structural components (Bradley et al 2009, Khakurel et al 2020), which has rendered many of these claimed "low-damage" technologies not yielding the desired "low-loss" seismic performance. While these low-damage technologies have started being adopted in many buildings in New Zealand in recent years, their application in general is still limited due to; absence of established design standards/guidelines, limited practicing engineers with required knowledge/expertise, perceived increase in the project cost when these technologies are adopted, and other non-technical reasons.

While the quest for novel low-damage structural and non-structural systems is continuing, engineers are also trying to explore means of achieving superior seismic performance by altering the existing seismic design philosophy. The basic objectives of most current seismic codes for buildings is to ensure continued operation in frequent earthquakes and life-safety in rare earthquakes. While the former (i.e., continued operation in frequent earthquakes) is achieved by providing sufficient elastic (i.e. yielding) strength, life-safety in rarer earthquakes is achieved by following capacity design to restrict inelastic deformation to well-detailed ductile plastic hinges. A common approach adopted by most seismic codes to achieve these dual performance objectives involves sizing the structural members for a reduced design seismic force which is considerably less than the elastic demand and detailing the designated plastic hinge regions adequately to sustain the required extent of inelastic deformation without compromising strength. The design seismic force is calculated using a response reduction factor (R) which, in the context of NZ seismic design standard NZS1170.5 (SNZ 2004), can be argued to be the ratio of the ductility factor (k_μ) and the structural performance factor (S_P). While this approach has proven to satisfy both of the above mentioned design objectives, it inherently attracts an undesired performance in the form of extensive damage in moderate earthquakes. As shown schematically in Figure 1 (Pampanin 2012), a larger force reduction factor (in lieu of a greater ductility capacity) leads to larger extent of damage in a design level of seismic action.

While it is widely accepted that a smaller force reduction factor (and hence aiming for a greater elastic/yielding strength) can reduce the extent of earthquake-induced damage, buildings are predominantly designed with a weaker but ductile structural system using a high response reduction factor because it is believed that reducing the design strength of a building significantly reduced the building cost. Nevertheless, the structural components comprise only a minor proportion of the total construction cost of buildings (Taghavi and Miranda 2003, Khakurel et al 2020). Moreover, it is also worth noting that the seismic capacity of a building is governed by the strength of a few structural load path members and the cost of these members contributes only a fraction of the structural cost of a building. The proportion of the structural material cost in the total project cost depends on several factors such as; occupancy class of the building, construction methodology, labour cost, soil condition, and non-structural components costs (Ang and Lee

2001, Ramirez and Miranda 2009). Note that for a code compliant building designed with a high response reduction factor, there is an additional structural material cost due to the stringent confinement detailing requirements (e. g. closely spaced stirrups for RC frames). Also, it is important to note that the major proportion of the structural material volume is concentrated in the floor slabs which are governed by gravity loads rather than the lateral seismic forces. These raise an undeniable argument that the total project cost of a building would not be overly sensitive to the seismic force reduction factor used in designing the building. Hence, improved seismic performance may be achieved, without prohibitively increasing their cost, by designing buildings with low strength reduction factors. However, current seismic codes do not enforce ductile detailing requirements for buildings designed with a low response reduction factor which results in buildings that respond elastically in a design level earthquake, but are likely to fail/collapse in a higher intensity earthquake because of their compromised inelastic deformation capacity. The seismic performance of conventionally designed elastic buildings (in a design level earthquake and beyond) can be significantly improved by ensuring capacity design (i.e. strong column-weak beam) and ductile detailing so that brittle failure is avoided in a higher intensity shaking (as shown in Figure 1).

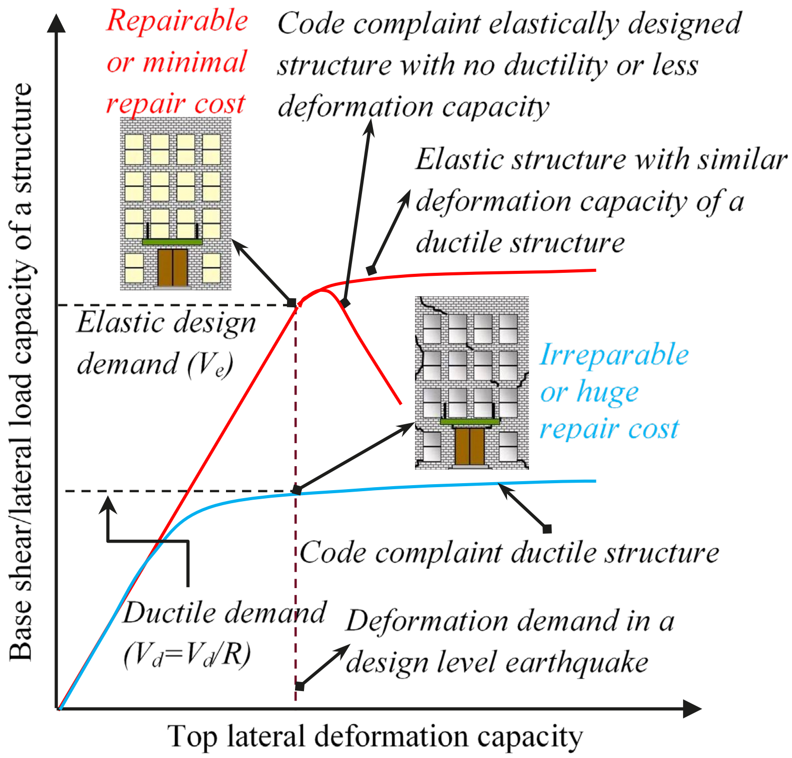


Figure 1: Performance of a code compliant building designed for different R factors (Pampanin, 2012)

When it comes to RC frame buildings, engineers seem to believe that there is no need to design these buildings with low response reduction factor (i.e. R less than two). This argument may be justified for; (i) high rise buildings because of the difficulty in providing for excessive elastic seismic design demand, (ii) countries where the seismic risk is low or not the first priority, and (iii) countries where the labour cost is cheap; rendering the structural material cost contributing significantly to the total construction cost. But for a seismically active country like New Zealand where majority buildings are low to medium rise and the post-earthquake recovery cost has been proved to be excessive, designing buildings to respond elastically in a design level earthquake and provide adequate detailing so that it can deform plastically in a higher intensity shaking can arguably yield huge benefits in terms of seismic loss/downtime reduction and improved societal resilience. Obviously, this will increase the structural material cost and the total project cost to some extent, which therefore raises a key research question: “are the low to medium rise stronger elastic concrete frame buildings really expensive to build?”

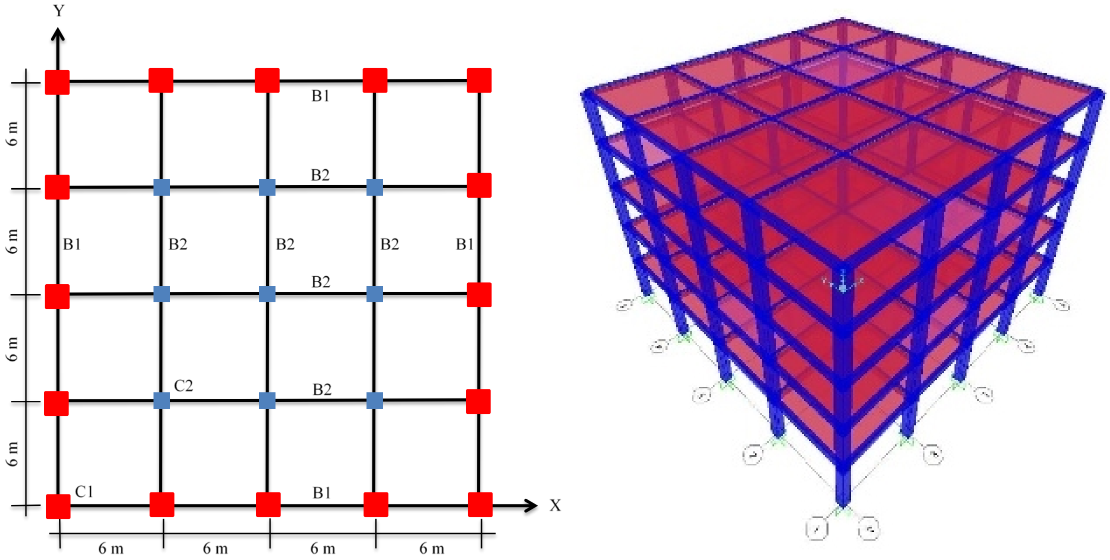
Hence, this research paper aims to determine not only if it is feasible to design stronger concrete frame buildings, but what implications can it have for the developers, design professionals as well as the clients. Note that the incumbent seismic design methods allow less stringent detailing when a smaller force reduction factor is used (in other words, when a greater design force is used). However, as the level of detailing (mainly governed by a small variation in the amount and arrangement of stirrups in the potential plastic hinge regions) causes trivial change to the cost of the project but contributes drastically towards ensuring life-safety at shaking intensities exceeding the DBE, there is little incentive to compromise the level of detailing when the force reduction factor is reduced. Hence, ductile detailing is retained in all designs despite the strength being calculated with different reduction factors.

The primary objectives of the research work reported in this paper are:

- To calculate the structural material cost of low and medium rise RC frame buildings designed for different response reduction factors and full ductile confinement detailing.
- To estimate the project cost for the investigated cases by utilizing the estimated structural material costs and the cost planning rates of non-structural elements, services, and other professional fees.
- To investigate the variation of the structural material costs and the total project cost for the designed building cases as a function of seismic force/response reduction factor.
- To summarize the advantages of stronger RC frame buildings designed to respond elastically in a design level earthquake.

2 DESIGN METHODOLOGY

To represent typical low and medium rise RC frame buildings in NZ, a four storey building (on soil type E in Wellington) and a ten-storey building (in Christchurch) were designed with different response reduction factors (R = 1, 3, 4 and 6) by satisfying the requirements of New Zealand concrete structures standard NZS3101 (SNZ 2006). All eight buildings were assumed to be square in plan with four bays in both directions, with each bay of span length 6 m and storey height of 3.6 m as shown in Figure 2. The overall structural system comprised of moment resisting frames in both directions with internal frames resisting predominantly gravity loads and perimeter frames resisting seismic lateral forces. The loading and material properties considered for the analysis and design are reported in Table 1. Some assumptions made in designing and comparing the costs of these buildings include (but not limited to); the floor slab thickness remains the same irrespective of different seismic demands, beam-column joints detailing contributes little to the building cost and is hence excluded from the cost estimation, and gravity loads are constant across the investigated cases.



(a) Typical plan (b) Finite element model

Figure 2: Typical layout of the office building considered for design and cost estimation

Table 1: Design requirements for the investigated building cases.

Loading requirements	**Seismic requirements**	**Material properties**	
Live load		Grade of concrete (f'_c)	40 N/mm^2
Roof: 2.5 kN/m^2,	Response reduction factor (R): 1, 3, 4 and 6	Grade of rebars (f_y)	300 N/mm^2 500 N/mm^2
Other floors: 3.0 kN/m^2			
Super imposed dead load	Zone factor: 0.3 and 0.4	Density of concrete (γ_c)	23.5 kN/m^3
Roof: ceilings and services: 0.25 kN/m^2; screed to falls: 1 kN/m^2	Near fault distance: 20 km	Modulus of elasticity of concrete (E_c)	29997 N/mm^2
Other floors: ceilings and services: 0.25 kN/m^2; partitions: 0.5 kN/m^2	Soil class: E	Modulus of elasticity of rebars (E_s)	2×10^5 N/mm^2

The design of the structural members was carried out as per capacity design principles (i.e. strong column-weak beam) by using design software (SAP 2018). The RC beam and column cross sections of a low rise building corresponding to different response reduction factors are summarised in Table 2. The inter-storey lateral drift including P-Δ effect of the designed building cases at the ultimate limit state was less than 2.5%.

3 COSTING METHODOLOGY

The costing for the investigated building cases was done by using estimation software “QV cost builder”, excel sheets, and manual calculations (Rawlinsons 2013). This software uses cost planning and detailed trade rates to estimate the cost of the project. The cost planning rates method provides the total cost of the materials, systems, and treatments which make all up the elements of a building. Also, the cost planning rate method is more accurate as opposed to solely relying on a square meter basis as it provides detailed costs for beams and columns, floors, finishes, and services etc. The estimation software also provides a detailed trade rate method where all components are broken down into material costs per square meter such as; reinforcing steel, cast-in-situ concrete, and precast concrete etc. For this study, the cost planning rates method was deemed sufficient in determining the total project cost of the investigated low and medium rise RC frame buildings. The following items were excluded in the cost analysis; (i) land and demolition, (ii) balconies, covered ways, parking areas, (iii) external services more than 3m from the outside face of the building, (iv) data and telephone services, (v) external works other that those immediately adjacent to the building, (vi) loose furniture, fittings and equipment, and (vii) goods and services tax. Professional fees (design engineers, architects, and project managers etc.) and preliminaries and general (P&G) fees were considered as 10% and 12.5% of the subtotal cost respectively, with the subtotal cost defined as the total project cost excluding the professional fees and P&G fees.

Table 2: Summary of cross section details of low rise concrete building designed for different R factors.

Response reduction factor (R)		**6**	**4**	**3**	**1**
Beam (B1) details	Depth (mm)	500	500	500	500
	Breadth (mm)	300	300	300	300
	Moment demand (kN-m)	252	357	453	1021
	Moment capacity (kN-m)	285	376	456	1101
	Rebar grade fy, (MPa)	300	300	300	500
	Required area of rebars (mm^2)	2238	2945	3573	5180
	Bottom rebar details	4D20+2D25	6D25	6D25+2D20	4D32+4D25
Column (C1) details	Depth (mm)	400	400	400	550
	Breadth (mm)	400	400	400	550
	Axial demand (kN)	1534	1657	1771	2437
	Moment demand (kN-M)	517	594	802	1828
	Rebar grade fy, (MPa)	500	500	500	500
	Required area of rebars (mm^2)	6240	7680	11840	17999
	Provided area of rebars (mm^2)	6283	7854	12868	19302

The costing for the eight building cases was split into non-structural and structural costs, with these primary components further broken down into various sub components. The non-structural components cost was calculated based upon price per square meter approach. The estimated non-structural cost of the investigated building cases was compared to the costing of similar office buildings and found to be consistent, therefore it assures the non-structural cost estimates to be reasonably representative. The structural material cost was estimated by using calculated quantities of the columns, beams, floor slabs, and foundations and cost planning rates. The pile foundation cost was assumed to increase or decrease in the same ratio as the primary columns cost ratio between different response reduction factors. Although this assumption will induce some error to the total project cost, it is legitimate to state that the validity of the research is not affected significantly as the point of interest is the percentage change in the total project cost. The costing details for a low-rise RC frame building designed for a response reduction factor four are presented in Table 3. Once the total project cost was known for each of the eight investigated building cases, the effect of response reduction factor on the total project cost was analysed.

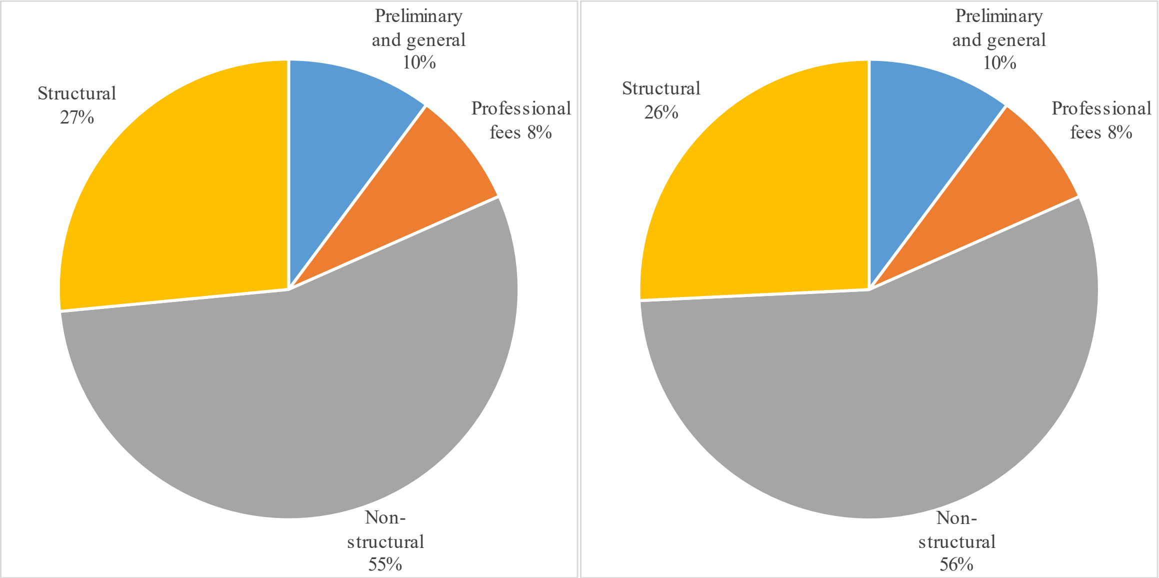
Table 3: Costing summary for a low-rise building designed for response reduction factor four.

Description	Rate	Quantity	Total (NZ$)	Notes
Structural material cost				
Columns	468	299.9	$140,400	Cost/m
Beams	420	657.7	$276,200	Cost/m
Floor slabs	203	1,323	$268,600	Cost/m^2
Ground floor slab	126	441	$55,600	Cost/m^2
Walls	62	1,232.64	$76,400	Cost/m^2
Sub-structure	106	1,831.84	$194,200	Cost/m^2
Total structural			$1,011,400	~26.5% of the project cost
Exterior fabric				
Roof	258	457.96	$118,200	Cost/m^2 (150mm roof slab)
Exterior walls	162	308.16	$49,900	Cost/m^2 (Graphex panels)
Internal finishing				
Stairs	2801	10.8	$30,300	Cost per meter rise
Interior walls	240	1,232.64	$295,800	Cost/m^2 (Partition walls)
Interior doors	30	1,831.84	$55,000	Cost/m^2 floor area
Floor finishes	230	1,831.84	$421,300	Cost/m^2 (Marble tiles)
Wall finishes	61	1,232.64	$75,200	Cost/m^2 (Standard Gib)
Ceiling finishes	51	1,831.84	$93,400	Cost/m^2 (standard plasterboard)
Fittings & fixtures	16	1,831.84	$29,300	Cost/m^2 (for office building)
Services				
Sanitary plumbing	70	1,831.84	$128,200	Cost/m^2 (Standard rate)
Mechanical services	220	1,831.84	$404,400	Cost/m^2 (Standard rate)
Fire services	14	1,831.84	$25,600	Cost/m^2 (Standard rate)
Electrical services	119	1,831.84	$218,000	Cost/m^2 (Standard rate)
Lifts & escalators	140,000	1	$140,000	Cost per lift (Assumed 1 Lift)
Drainage	9	1,831.84	$16,500	Cost/m^2 (Standard rate)
Total non-structural			$2,101,100	~55.1% of the project cost
Sub Total			$3,112,500	
Exterior works & sundries				
Contractor P&G + Overhead			$389,100	12.5% of Sub Total
Professional fees			$311,300	10% of Sub Total
Total project cost			**$3,812,900**	~$2,080/m^2 floor area

4 RESULTS AND DISCUSSION

4.1 Structural and non-structural cost proportions

The breakdown of different cost components for the low and medium rise buildings designed with response reduction factor four is presented in Figure 3. It can be confirmed that the structural material cost of a RC frame building designed according to New Zealand standards is approximately 27% of the total project cost. Note that there can be another 5% variation in the predicted structural material cost depending on the importance of the building, cost inflation of the materials and labour, and many other non-technical reasons. Also, it can be seem that the non-structural cost proportion is more than half of the total project. While this cost breakdown is true for New Zealand, its validity in other countries needs to be further investigated.



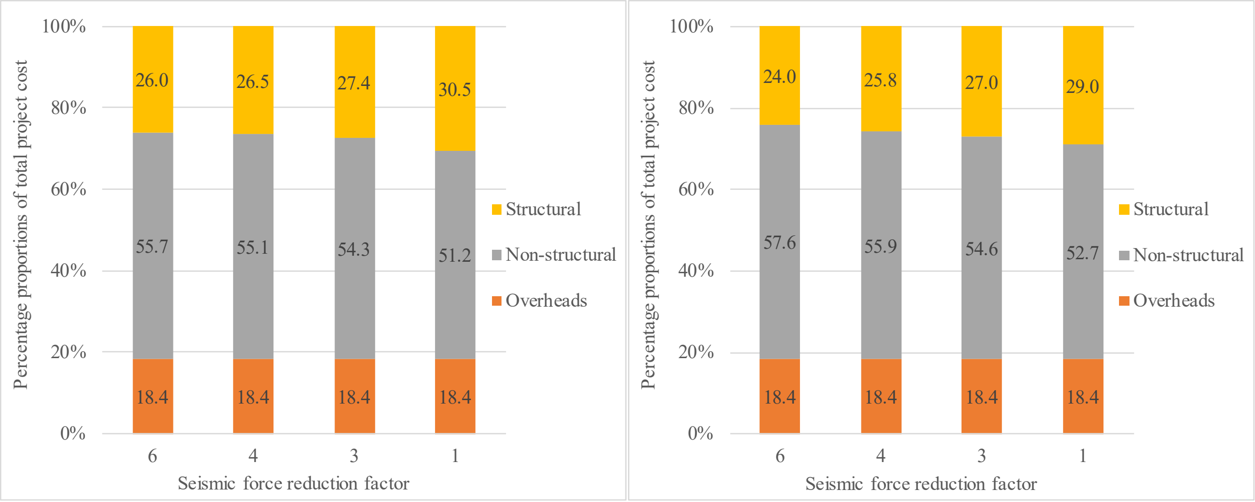
(a) Low rise buildings (b) Medium rise buildings

Figure 3: Cost breakdown of concrete frame buildings designed with an R factor of four

4.2 Cost variation as function of seismic force/response reduction factor

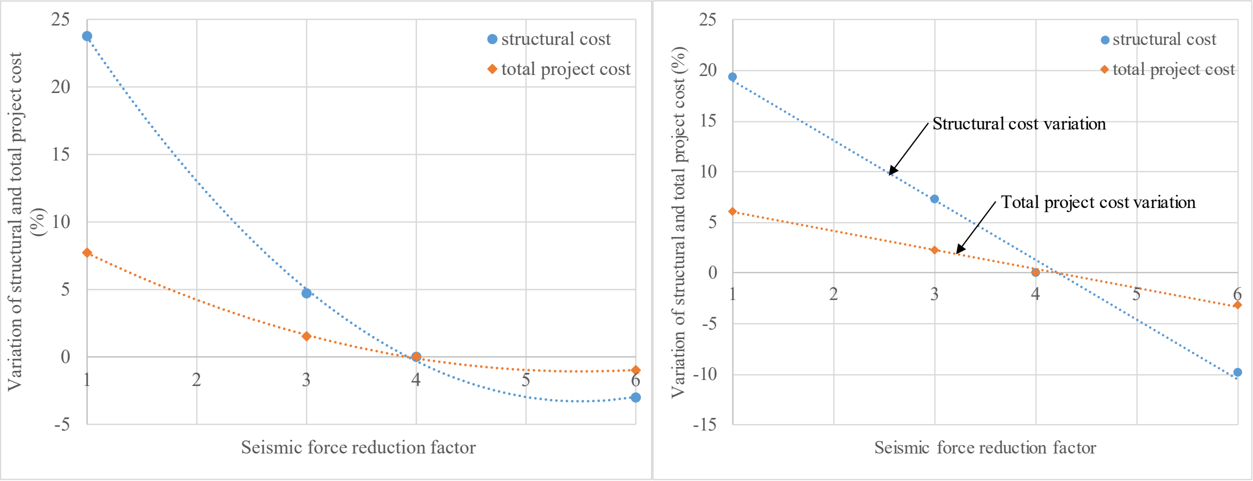
Figure 4 provides an overview of three major components (i.e. structural, non-structural, and overheads) cost proportions of RC frame buildings designed with different response reduction factors (R = 6, 4, 3 and 1). Here, the overhead cost is a combination of the professional fees and P&G fees. It is clear from the figure that as the design response reduction factor is decreased the structural material cost proportion is increased.

The percentage change in the structural material and total project costs due to increase/decrease of seismic force reduction factors when compared to the building designed for an R factor of four is shown in Figure 5. Best fit relationship between the structural material/total project cost change and seismic force reduction factor is shown in the plots for both the low and medium rise buildings. While the variation is close to linear for medium rise buildings, the cost of low-rise buildings increase exponentially with reduction of force reduction factor. Note that the low-rise building was assumed to be located in Wellington with the most demanding soil type, which results in a larger base shear coefficient when compared with the medium rise building which was designed with its location based in Christchurch. Hence, the increased sensitivity of the cost to the force reduction factor for low-rise buildings compared to the medium-rise buildings may be attributed partly to the higher degree of conservatism in the design of the low-rise building. The variability in costs between Wellington and Christchurch also contributed to the minor difference in the trend of the structural and total project cost change. Note that while the structural cost can increase by 20-25% when the building strength is quadrupled (i.e. force reduction factor changing from 4 to 1), the total project cost increases by only 6-8%.



(a) Low rise buildings (b) Medium rise buildings

Figure 4: Components of the total project cost for the low and medium-rise building design cases



(a) Low rise buildings (b) Medium rise buildings

Figure 5: Variation of structural material and total project cost as function of response reduction factor

As the structural material and labour costs can vary significantly from country to country, it is recommended that relevant costing rates be checked against those of New Zealand before extrapolating the findings of this research work. A recent study of the breakdown of construction costs in United States (Porter 2020) has reported that the cost of materials attributable to lateral load resisting components only (excluding the gravity load system) is 2% of the construction cost of a typical new building and even doubling this material cost implies 1% increase in the total construction cost. An example of countries where these findings would not be readily applicable are India and China, where the cost of labour is significantly cheaper compared to New Zealand.

4.3 Effect of stronger elastic buildings on its life cycle cost

As stronger buildings can withstand larger seismic force, the elastic response of such buildings in moderate-large earthquakes lead to much smaller displacement compared to the nonlinear response of weaker buildings. Although in the examples shown in this paper the strength of beams and columns was changed mainly by altering the amount of reinforcement, they could have easily been achieved by different combinations of cross-section dimension and reinforcement amount. Note that an increase in section size to aid strength gain also invariably increases the section stiffness, which can further reduce the displacement response of the buildings. The reduced displacements lead to less structural damage; thereby resulting in significant savings in damage repair cost during the buildings' life. Not only is the building protected from the irrecoverable structural damage, the reduced displacements also protect most drift-sensitive non-structural components from damaging in minor-moderate earthquakes and reduce the extent of non-structural damage in major earthquakes. This is extremely relevant as the cost to replace the non-structural components is more than 50% of the total project cost. By designing a stronger building, the marginal increase in the initial project cost will certainly pay dividends in the long-run by reducing life cycle costs. Insurance companies will reduce their risk occurring from structural damage, thereby saving costs on future claims. This arguably justifies a reduction in insurance premium for stronger buildings.

The outcome of this research work can also be used to take important policy decisions related to the seismic design philosophy. The present seismic design ensures minimal loss of life, however, often the cost to repair the damaged structures can be prohibitively high. This research shows that if buildings are designed such that they respond elastically in design level earthquakes (while retaining ductile detailing), the initial building cost increases slightly but it significantly reduces the damage repair costs and business interruption costs in future earthquakes. This information would be useful to the investors who are willing to invest 6% to 10% more in the CAPEX cost to reduce the OPEX cost. The clients in the active seismic regions will take note of the high-seismic risk and be prepared to pay the extra CAPEX cost to reduce this risk by constructing stronger buildings.

Although the life cycle cost benefits far outweigh the initial investment, there needs to be an implementation of fiscal incentives for the developers/owners to invest the additional amount to build stronger buildings. The incentives could be in the form of reduced insurance premium, increased rental/sale values or building tax/rate rebates. The increase in personal safety, reduction in business downtime and the non-structural damage are key features of stronger and stiffer buildings. With the obvious reduction of risk and increased assurance of business continuity in earthquakes, there is enough justification for insurers/councils to provide insurance/tax rebates and for tenants/buyers to be willing to consider paying slightly more for stronger buildings. These benefits strongly justify the additional initial cost to design and build stronger buildings, and this could be advocated as a means of a simple and affordable low-damage seismic design alternate.

5 CONCLUSIONS

This research investigated the effect of the seismic response reduction factor on the structural material and the total project cost of low and medium rise concrete frame buildings designed according to New Zealand standards. The feasibility of designing concrete frame buildings (with ductile detailing) to respond elastically in a design level earthquake is also explored. The designed building cases are assumed to be located in Wellington and Christchurch, and this allowed for the comparison of the building component sizes and the associated costs between two cities with different seismicity. Structural material and total project costs are calculated using cost planning rates and estimated material quantities. Based on the cost analysis, the following conclusions are drawn:

- Based on market rates used in New Zealand a few years ago (the rates must have increased since), the structural cost contributes around 25% of the total project cost for new low and medium rise RC frame buildings.
- Changing the response reduction factor ($R= k_\mu/S_p$) from a value of four to one, the structural material cost increased by about 20%, and the total project cost increased by about 7% (on average) for the

investigated building cases. Note that a study based on construction costs in the United States has claimed the increase in construction costs will increase only by about 1% if the material costs for a lateral load resisting components in a building is doubled to increase the building's strength and stiffness (Porter 2020). As the total project cost increase is modest and the associated gain in seismic performance is significant, it seems desirable and financially feasible to build low and medium rise concrete frame buildings designed to respond elastically (or with minimal inelastic response causing no downtime for repair) in a design level earthquake.

- The use of lower response reduction factor in the design will protect the building structure from damaging (hence avoid structural repair costs) during moderate seismic events and also reduce damage to drift-sensitive non-structural components to a greater extent. The cumulative reduction in seismic losses (in the form of damage repair and business interruption costs) through the building life can be far greater than the insignificant rise in the initial cost.
- This research forms the qualitative basis for clients, industry professionals and policy makers to build stronger and stiffer buildings in the interest of protecting structural and non-structural components in future earthquakes. Nevertheless, to instil greater confidence the reduction of seismic losses and downtime of buildings with different levels of strengths should be quantified in further studies.
- As stronger and stiffer buildings contribute positively to the societal seismic resilience, property developers and building owners should be given incentives to invest small additional CAPEX cost to build stronger and stiffer buildings.

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