How would changes to serviceability limit state design criteria impact likely repair costs?

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ABSTRACT

The earthquake engineering community is currently grappling with the need to improve the post-earthquake reparability of buildings. As part of this, proposals exist to change design criteria for the serviceability limit state (SLS). This paper reviews options for change and considers how these could impact the expected repair costs for typical New Zealand buildings. The expected annual loss (EAL) is selected as a relevant measure or repair costs and performance because (i) EAL provides information on the performance of a building considering a range of intensity levels, (ii) the insurance industry refers to EAL when setting premiums, and (iii) monetary losses are likely to be correlated with loss of building functionality. The paper argues that because the expected annual loss is affected by building performance over a range of intensity levels, the definition of SLS criteria alone may be insufficient to effectively limit losses. However, it is also explained that losses could be limited effectively if the loadings standard were to set the SLS design intensity considering the potential implications on EAL. It is shown that in order to achieve similar values of EAL in Wellington and Christchurch, the return period intensity for SLS design would need to be higher in Christchurch owing to differences in local hazard conditions. The observations made herein are based on a simplified procedure for EAL estimation and hence future research should aim to verify the findings using a detailed loss assessment approach applied to a broad range of case study buildings.

1 INTRODUCTION

Most international codes currently require consideration of at least two limit states. In New Zealand, the loadings code NZS1170.5 specifies design criteria for an ultimate limit state (ULS), aimed at limiting the likelihood of structural instability and loss of life, and a serviceability limit state (SLS) aimed at ensuring the structure or part can continue to be used without requiring repair (sometimes referred to as SLS1 criteria). The loadings standard also identifies a second type of serviceability limit state (SLS2) that is aimed at maintaining operability but not all building typologies are designed for this limit state.

In order to reduce the damage and disruption to buildings in future earthquakes, the industry has been proposing changes to serviceability limit state design requirements. An initial proposal to change SLS requirements was made by Moore (2018) who suggested that a SLS design intensity be set with return period of 50 years and that a drift limit of 0.25% be imposed. Pettinga (2018) also supports an increase of the return period intensity for the serviceability limit state from 25 years to 50 years, arguing that this would provide a simple means of reducing damage and would align better with seismic design practice in California and Japan. Pettinga shows that by increasing the SLS design return period to 50 years and imposing a new SLS drift limit of 0.5%, improved building performance would result, with the on-set of damage being less likely in frequent earthquakes and limited ductility demands expected in rare ULS intensity shaking. These valuable contributions to the literature highlight the need for improved SLS design provisions and demonstrate that two means of reducing damage would be to revise the return period and impose a new drift limit for SLS design. This paper encourages the engineering community to consider a risk-based approach to help identify suitable changes to the SLS design criteria and sets out a possible framework for doing so.

2 FACTORS AFFECTING LOSSES AND DAMAGE

Figure 1 highlights a number of factors affecting the damage and losses to be expected over the lifetime of a building. The figure shows that to quantify likely losses, one will require information on the seismic hazard at the site (providing information on the return period of different levels of shaking intensity) and then the likely response of the building for different levels of shaking intensity should be estimated. If a building experiences large storey drifts and floor accelerations, high levels of damage and repair costs would naturally be expected. However, the figure shows that loss estimation also considers the likelihood of building components being damaged, as a function of engineering demand (such as peak storey drift and floor acceleration). This likelihood, or probability, is typically quantified using vulnerability functions such as those shown in the bottom left of Figure 1. Consequently, design choices affecting the vulnerability of structural and non-structural components in the building will also impact the expected damage and repair costs. For instance, even if a building experiences large drift demands, it may not be significantly damaged if the building possesses more resilient (well detailed) structural and non-structural components.

In relation to the values of storey drift that are likely to trigger the need for repair works, there is an increasing amount of evidence in the literature that suggests that the drift limit for SLS design would need to be very low for some building components. For instance, Table 1 reports the median value of drift observed to cause damage to a selection of non-structural elements and it can be seen that a drift limit of 0.25% could represent a non-conservative (i.e. fairly reasonable) estimate of the drift at which damage could initiate. However, as discussed in Sullivan et al. (2020), because there are also a number of building components that are well detailed so that the drift required to cause damage is greater than 0.5%, a more rational approach would be to set the SLS drift limits as a function of the drift capacity of the building components. This would require new industry guidance on the drift capacity of different building components but would also allow for more flexible seismic design strategies, with more flexible structural systems allowed if it can be shown that the building components are sufficiently deformable.

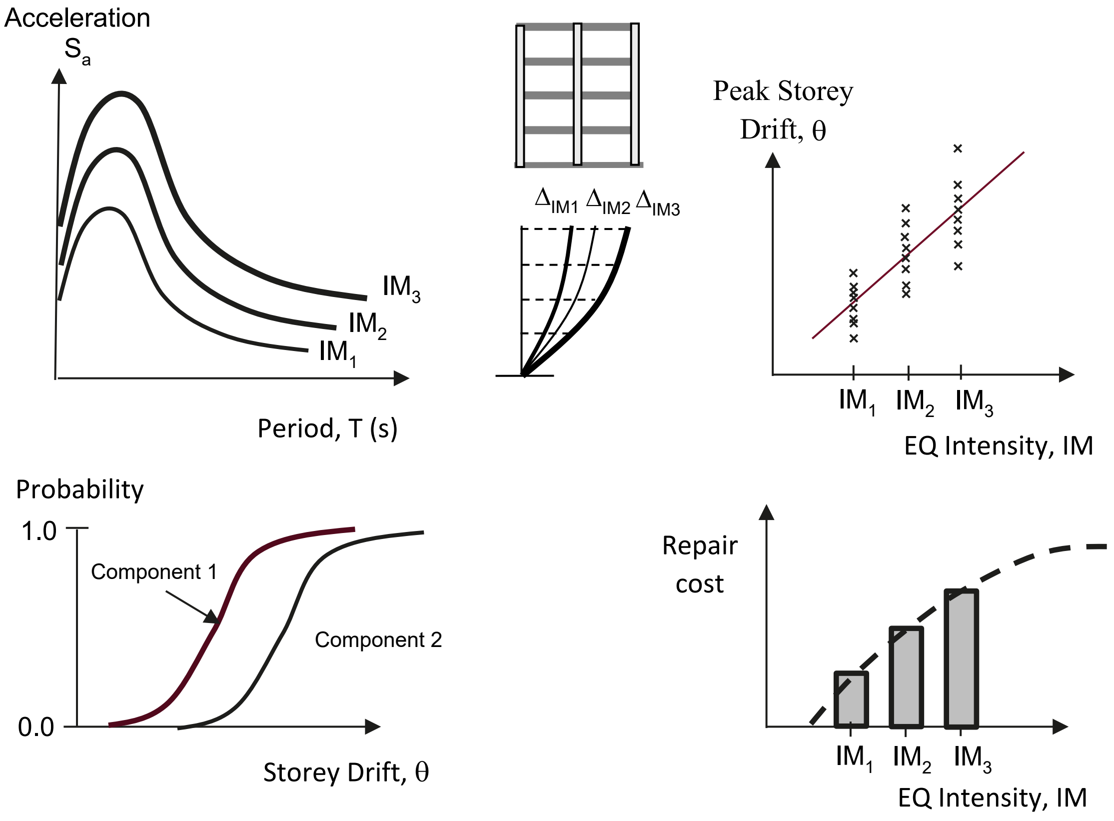

Figure 1: Overview of process used to quantify the expected annual loss (EAL) for a building.

Table 1: Storey drift capacity observed from experimental testing for a range of common drift-sensitive non-structural elements

Non-Structural Element Type	**Median drift at which initial damage observed**	**Reference**
Solid clay brick infill walls	0.14%	Sassun et al. (2014)
Curtain wall glazing*	0.35%	Arifin et al. (2020)
Plasterboard partition walls	0.29%	Davies et al. (2011) Mosqueda (2016)

** Corresponding to loss of water tightness. Significantly higher values could be expected for different types of curtain wall glazing systems*

The bottom right part of Figure 1 also shows that the repair costs will naturally tend to increase as a function of shaking intensity, with a maximum repair cost being the building replacement cost. Since the intensity of shaking that a site will experience cannot be known in advance of an earthquake, it is not rational to quantify performance in terms of expected losses at a single intensity level. Guidelines, such as FEMA P-58, do indicate how the repair cost estimated for different intensity levels can be multiplied by the annual probability of each intensity level occurring, with the sum providing the expected annual loss (EAL). The EAL, which is sometimes referred to as the average annual loss by the insurance industry, provides an indication of performance across a large range of intensity levels and thus appears a rational measure of seismic risk, particularly for what regards serviceability objectives. As such, this paper will consider how different approaches to SLS design could affect the EAL.

When quantifying losses, one can identify so-called “direct losses” associated with the cost of repairs to the building and “indirect losses” due to external factors that also affect losses. Indirect losses are very difficult to quantify since they can arise due to a myriad of events, such as damage to neighbouring buildings or disruption to access routes in the vicinity of the building. While Moore (2018) provides some useful discussion on indirect losses, the term EAL used in this paper is referring to direct losses that could be estimated as a function of expected building damage.

While the focus in this paper will be on impact of design decisions on the EAL, it is also recognised that the time required for functional recovery may be of more interest to commercial building owners and occupants. Research into means of quantifying the time required for function recovery are still being developed but one could expect some correlation between the expected annual loss and the expected annual time lost (EATL) to functional recovery. Future research should therefore aim to consider how design criteria could also impact on the EATL.

3 RELATING A LIMIT-STATE DESIGN APPROACH TO VALUES OF EAL?

Rigorous evaluation of the EAL is a time-consuming process, requiring non-linear time-history analyses to be conducted at multiple intensity levels, development of an inventory of damageable building components with associated vulnerability and consequence (loss) functions and Monte-Carlo simulations to account for uncertainties, with integration of results considering the local hazard (refer FEMA P-58). However, a number of procedures have been published to permit simplified estimation of the EAL. Figure 2 indicates the building loss model assumed in the procedure that will be utilised here, referred to here as the limit-state-loss approach from Sullivan (2016).

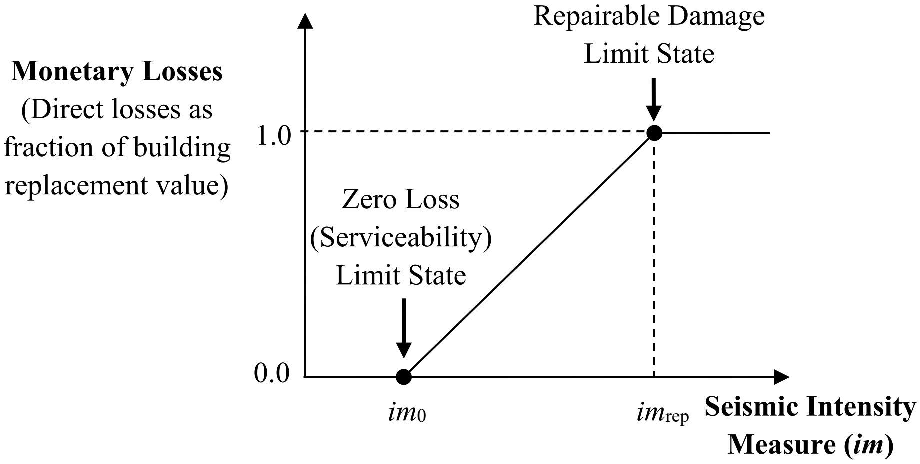

Figure 2: Bilinear loss versus intensity model assumed for simplified assessment of EAL.

The loss model shown in Figure 2 is anchored to losses at two limit states; the first is referred to in the figure as the zero loss limit state, but could also be referred to as the serviceability limit state, and it refers to the point at which the first signs of damage requiring repair would begin to appear. The intensity at which the zero-loss limit state is reached is denoted as im_0. The model then presumes that losses increase linearly as a function of intensity until the expected repair costs correspond to the replacement cost. This second point was referred to as the repairable damage limit state according to Sullivan (2016).

By combining the loss model with a simplified seismic hazard model for a site, Sullivan (2016) shows that the EAL can then be found from Eq.(1).

$$EAL = \frac{\left(\lambda_0 - \lambda_{rep}\frac{im_{rep}}{im_0}\right)}{\left(1 - \frac{ln\left(\frac{im_{rep}}{im_0}\right)}{ln\left(\frac{\lambda_0}{\lambda_{rep}}\right)}\right)\left(\frac{im_{rep}}{im_0} - 1\right)} - \frac{(\lambda_0 - \lambda_{rep})}{\left(\frac{im_{rep}}{im_0} - 1\right)} + \lambda_{rep} \tag{1}$$

where λ_0 and λ_{rep} are the mean annual rates of exceeding the zero-loss and replacement loss states respectively, and the ratio im_{rep}/im_0 is the ratio of the intensity values expected to cause the two key loss states to be exceeded (refer Figure 2). Note also that λ_0 and λ_{rep} can be obtained simply as $1/T_{R,0}$ and $1/T_{R,rep}$ respectively, where $T_{R,0}$ and $T_{R,rep}$ are the return periods of ground motion shaking at the zero-loss and replacement limit states respectively.

While the loss model shown in Figure 2 and the simplifications made to arrive at Equation 1 are very approximate, Sullivan (2016) found that EAL estimates obtained using the approach were quite similar to those obtained via rigorous loss assessment for a range of building structures. Cardone et al. (2017) also extended the approach to account for differences in damage patterns over the height of a building and differences in building behaviour in orthogonal directions. However, the expression for EAL given by Equation 1 will be useful here for highlighting the potential impact of different SLS design strategies on building performance.

4 ESTIMATING THE IMPACT OF DIFFERENT SLS DESIGN APPROACHES ON THE EXPECTED ANNUAL LOSS

In order to estimate the impact that different SLS design approaches could have on the expected annual loss, it will now be assumed that the serviceability and ultimate limit states defined in NZS1170.5 are practically equivalent to the zero-loss and repairable damage states respectively. As the limit states in NZS1170.5 have not actually been defined with relation to repair costs, one should expect that the actual loss model would differ from that adopted here. However, conceptually it is considered reasonable to expect that losses will be zero until the SLS is reached and that if drifts reach ULS limits, the decision may well be made to replace the building following an earthquake (as was decided in Christchurch following the Canterbury earthquakes).

The first approach that will be investigated is to simply increase the return period for which SLS design is conducted. Three scenarios are considered: (i) Tr = 25years, (ii) Tr = 50 years, and (iii) Tr = 100years. Utilising the simplified expression from Equation 1 together with data on the hazard for sites in Christchurch and Wellington obtained following the process described in Yeow et al. (2018), EAL estimates are obtained for a the different SLS design scenarios in different parts of the country and are reported in Table 2.

Reviewing the results shown in Table 2, one observes that by increasing the return period for the SLS design limit state, significant reductions in losses can be expected. However, it is also evident that the building location (and more specifically, the local hazard) can greatly affect the repair losses expected. For a SLS design return period of T_r = 25 years, the expected annual loss predicted for Wellington design solutions would be 70% those of medium-long period buildings designed in Christchurch.

Table 2: Illustrating the potential impact of the SLS design return period on expected annual loss.

		Expected Annual Loss* (% building replacement cost)		
Location	**Building Period**	**SLS T_r = 25yrs**	**SLS T_r = 50yrs**	**SLS T_r = 100yrs**
Christchurch (subsoil class D)	T = 0.5s	0.93%	0.66%	0.46%
	T = 1.0s	0.93%	0.66%	0.46%
	T = 2.0s	0.93%	0.66%	0.46%
	T = 4.0s	0.93%	0.65%	0.46%
Wellington (subsoil class C)	T = 0.5s	0.77%	0.58%	0.43%
	T = 1.0s	0.74%	0.57%	0.43%
	T = 2.0s	0.69%	0.56%	0.42%
	T = 4.0s	0.65%	0.54%	0.42%

** To be considered upper bound estimates of EAL because it has been presumed that building design is governed by seismic requirements and that replacement is required for ULS loading with 500 year return period and that the zero-loss limit state (refer Figure 2) is passed exactly at the SLS return period indicated.*

Differences in seismic hazard between Wellington and Christchurch are responsible for the significantly lower expected losses expected for buildings in Wellington designed with the same SLS and ULS criteria. Figure 3 shows the annual rate of exceeding different levels of spectral acceleration for difference New Zealand cities as adopted in this study (using hazard data as per Yeow et al. 2018). The plots have been annotated to indicate return periods corresponding to 50 years and 500 years. Note that while the 500 year (ULS) intensity level is larger in Wellington than in Christchurch, the opposite is true for the 50 year demands. Consequently, there is a higher likelihood of moderate intensity shaking levels in Christchurch and for this reason, the expected annual losses values reported in Table 2 were higher for Christchurch than for Wellington, even though the return periods of the SLS and ULS design limit states were the same.

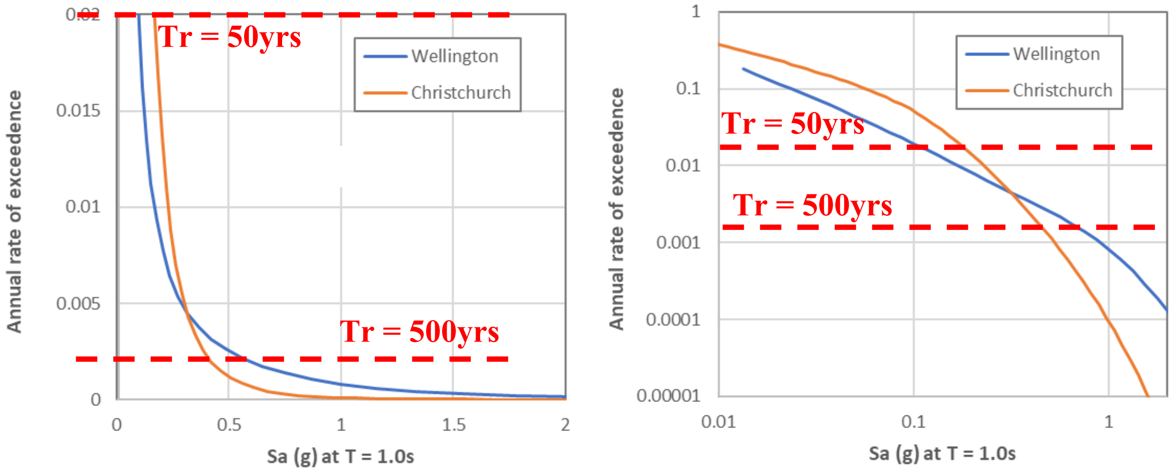

Figure 3: Annual rate of exceeding different levels of spectral acceleration (for T=1.0s) for sites in Wellington and Christchurch (linear scale on left and logarithmic scale on right).

In Europe, a different approach is used to specify the design intensity for what is equivalent to the serviceability limit state used in New Zealand. In Eurocode 8 (CEN 2004), the damage limitation state design intensity is set as a fraction of the ultimate limit state design intensity (using a value v in Cl.4.4.3.2). Eurocode 8 does not define exact values for the fraction to be used, but does suggest that values in the order of 0.4 to 0.5 may be appropriate. Interestingly, the Eurocode 8 also defines drift limits for the damage limitation state as a function of the deformability of the building components.

If a similar approach to that used in Europe were adopted in New Zealand (but with values of v defined after reviewing the results of rigorous loss assessments), it is apparent that the design standards could ensure more uniform values of expected annual loss for different regions. For example, Figure 4 shows the SLS design intensity, as a fraction of the ULS design intensity that would be required to limit the EAL to 0.65%. Similarly, Figure 5 shows the fractions that would be required to limit the EAL to 0.5%. As these fractions have been identified through trial and error utilising the EAL expression presented earlier in Equation 1, they should only be considered as approximate. However, the conceptual basis of the figures should be reasonable and shows that a fractile approach to the SLS intensity, similar to that used in Europe, could permit more effective control of seismic risk, without significantly complicating the design process.

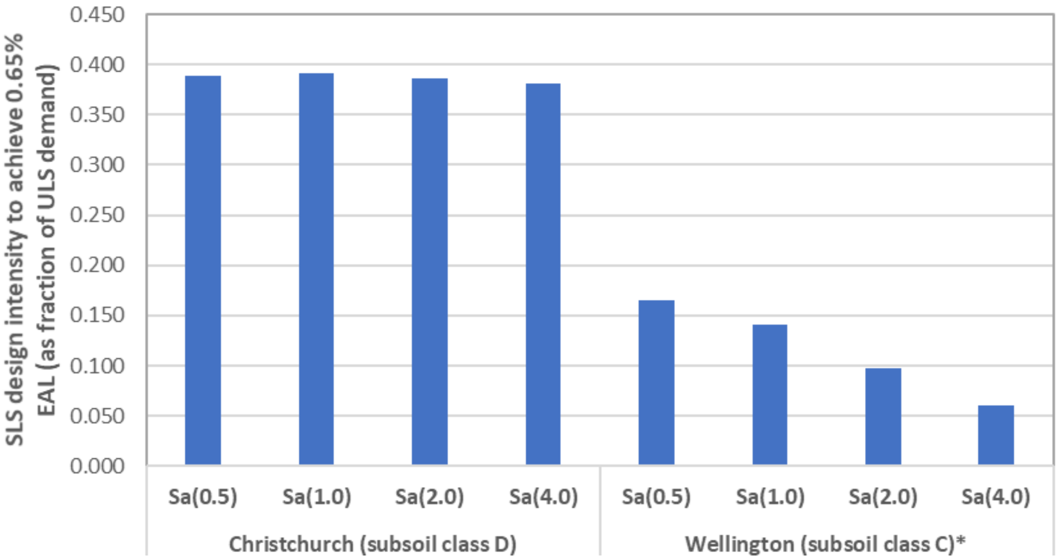

Figure 4: Fraction of the ULS design intensity that to specify for SLS design in order to limit EAL to 0.65% (values are approximate only and would need verification via rigorous loss assessment).

The results in Figures 4 and 5 also reveal that the SLS design intensity would most likely have a significant impact on new buildings in Christchurch but would be less critical for those in Wellington. As such, it would appear that any changes to SLS design requirements should not have the same impact on building designs around the country, since the ratio of spectral demands associated with frequent return periods to those at 500 years (ULS) vary considerably.

An alternative means of implementing a loss-targeted approach such as that described above in New Zealand would be for the loadings standard (NZS1170.5) to directly specify Z-values for the SLS design intensity such that, together with the ULS requirements, code-compliant buildings are assured of limiting the EAL to acceptable values. This would effectively mean that the Z-values for SLS loading would not correspond to the same return period of shaking in different cities but this point is unlikely to be of concern to designers.

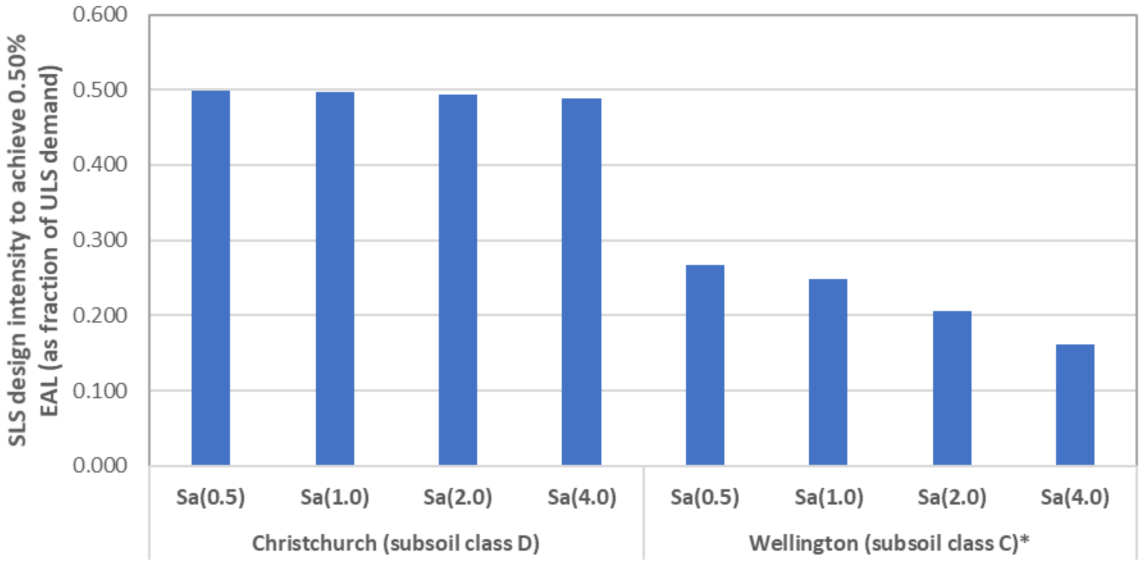

Figure 5: Fraction of the ULS design intensity that to specify for SLS design in order to limit EAL to 0.50% (values are approximate only and would need verification via rigorous loss assessment).

5 DISCUSSION AND CONCLUSIONS

Changes to serviceability limit state criteria are considered necessary in New Zealand to help reduce the disruption and losses caused by future earthquakes. This paper has briefly reviewed options for change and has considered how SLS requirements could affect the expected repair costs for typical New Zealand buildings. The expected annual loss (EAL) is selected as a relevant measure or repair costs and performance here because (i) EAL provides information on the performance of a building considering a range of intensity levels, (ii) the insurance industry refers to EAL when setting premiums, and (iii) one could anticipate that monetary losses are somewhat correlated with loss of building functionality. The paper points out that because the expected annual loss is affected by building performance over a range of intensity levels, the definition of SLS criteria alone may be insufficient to effectively limit losses. However, it is also explained that the EAL could be limited effectively if the loadings code were to set the SLS design intensity considering the potential implications for expected annual losses. It is shown that in order to achieve similar values of EAL in Wellington and Christchurch, the return period intensity for SLS design would need to be higher in Christchurch owing to differences in local hazard conditions. It is also shown that the suitable intensity for SLS design could be defined by the code after considering the local seismic hazard and desired maximum acceptable level of EAL.

The observations made herein are based on a simplified procedure for EAL estimation and hence future research should aim to verify the findings using a detailed loss assessment approach applied to a broad range of case study buildings. Furthermore, the implications of introducing low-damage building design solutions, in which the repair cost at ULS shaking can be expected to be significantly lower than the replacement cost, should be investigated.

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