ADVANTAGES OF USING THE SIMPLIFIED LATERAL MECHANISM ANALYSIS (SLaMA) TECHNIQUE IN THE ASSESSMENT OF NEW ZEALAND 1960s REINFORCED CONCRETE FRAME BUILDINGS

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As structural engineers assessing existing buildings, one of the greatest challenges is how to accommodate assumptions on unknown – and even unknowable – building properties within our analysis. How to judge when our analysis ceases to be a sufficiently accurate approximation of reality.

The authors have addressed this challenge in a recent assessment of a large 1960s New Zealand building, assessed using the Simplified Lateral Mechanism Analysis (SLaMA) technique and using the Non Linear Time History Analysis (NLTHA) technique. The findings of this case study building are presented in the paper.

The SLaMA technique is compared to NLTHA and both methods critiqued. A commentary on where the authors consider the SLaMA technique provides a better insight into building behavior and likely strengthening requirements is provided. Comparative findings from the two full, independent assessments (one using SLaMA, the other NLTHA) on the case study buildings are presented.

Commentary is also given on unpredictable nature of commonly occurring non-structural design and construction practices from the time, and the impacts that these have on the structure, and on the reliability of structural assessment.

Background – The New Zealand Seismic Assessment Environment

New Zealand is currently going through the process of assessing its existing building stock in reaction to the Earthquake Prone Building provision of the 2004 Building Act. This process has been heavily influenced by learnings from earthquakes from 2010 to 2016 and captured in a set of technical guidelines (*The Seismic Assessment of Existing Buildings, MBIE, 2017*).

The Guidelines recommend that Simplified Lateral Mechanism Analysis (SLaMA) be used at least as an initial step in any detailed assessment.

A Short Summary of SLaMA

SLaMA is a simple non-linear pushover assessment focused on assessing structures at a sub-system level. Its focus is on understanding failure hierarchies, and then translating the subassembly behavior upwards to full building behavior.

The SLaMA methodology as set out in the Guidelines has six primary steps:

1. Assess the structural configuration and load paths to identify key structural elements, potential structural weaknesses and severe structural weaknesses.
2. Calculate the relevant probable strength and deformation capabilities for the individual members
3. Determine probable inelastic behavior of elements by comparing probably member capacities and evaluating the hierarchy of strength.

4. Assess the subsystem inelastic mechanisms by extending local to global behavior.
5. Form a view of the potential governing mechanism for the global building by combining the various individual mechanisms.
6. Determine equivalent SDOF system, seismic demand and *%NBS*.

The final output of a SLaMA assessment is a simplified backbone curve for the system, similar to the example shown below.

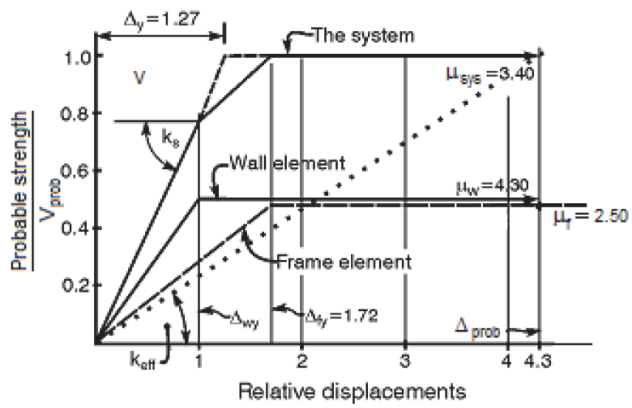

Figure 1. Sample SLaMA backbone curve, (MBIE Seismic Assessment Guidelines)

Accounting for Uncertainty.

The outcome of any building seismic assessment in New Zealand is ultimately condensed down to the provision of a building rating, represented as a Percentage of New Building Standard or *%NBS*. While this single number rating is very clear and simple for communication with the general public, it does not adequately convey the uncertainty inherent in the assessment process.

Attempts are often made by practicing engineers to convey the uncertainty associated with *%NBS*. Methods such as the 'expected performance' diagrams in the Guidelines are used to try to reintroduce this 'fuzziness' back into the reporting of building rating.

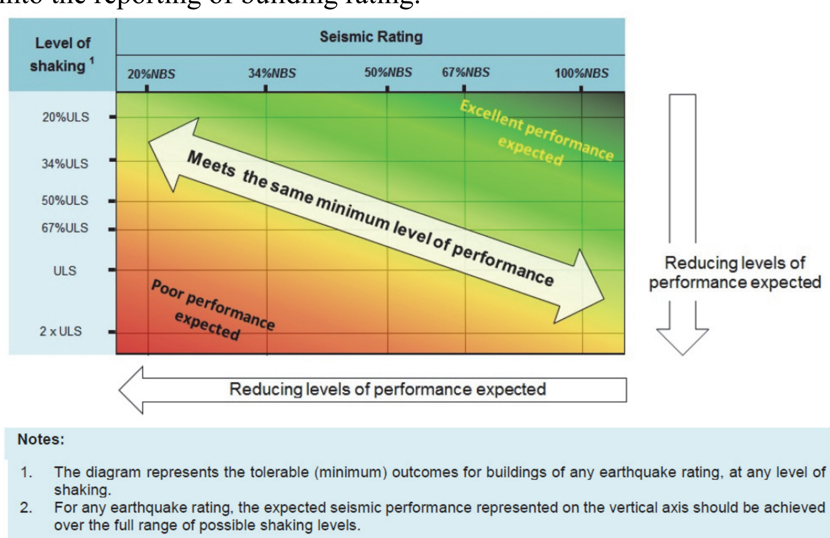

Figure 2. Diagram used to convey uncertainty in the New Zealand Seismic Assessment Guidelines

Perhaps less effort is exerted than should be by practicing engineers in managing the deficiencies in their own predictions of building behavior. Most engineers readily acknowledge that we are dealing with uncertain inputs. We know that the earthquake shaking will not be as predicted, that material properties will be different than assumed, that details may not be constructed as drawn, and that alterations may have changed the building.

However, while we openly acknowledge these uncertainties, we will typically then undertake two processes which serve to artificially conceal this unpredictability:

1. Undertaking detailed computer analyses that require – as a practicality – simplification of inputs down to single assumed values (or at best, considering limited sensitivity studies).
2. Attempts to evaluate non-linear systems by analytical means – which can lead to suppression of the visibility of alternate failure mechanisms.

Unpredictability in Existing Building Assessment as Compared to New Build

In new builds, unpredictability is deliberately controlled through a number of approaches built into any good design.

- **Adoption of robust load paths**: Priority is given to robustness of gravity load paths, especially those influenced by lateral forces or displacements. Direct simple vertical load paths are encouraged and non-tied-in seating details or other gravity systems potentially subject to sudden failure are avoided.
- **Adoption of dependable failure hierarchy**: Capacity design principles are strongly encouraged, as are explicit and preferable failure hierarchies such as beam-hinging frames. Undesirable step-change failure mechanisms such as soft-stories are suppressed.
- **Use of controlled materials**: Clear material specifications of relatively predictable materials provide reasonable surety of material properties, with calibration of control features such as over-strength factors aligned to these material properties.
- **Use of ductile materials**: Ductile materials (and detailing) is heavily favored, giving structural systems the ability to redistribute load to deal with unexpected non-linearities.
- **Limitation of non-structural elements impacting structure**: Care is generally taken through the design process to avoid the impact out outside influences on the structure (such as infill walls, surrounding ground, adjacent buildings, and stairs).

All of the above serve to limit the non-predictability of the structural *system*, even when individual elements may be non-linear.

For example, a new building moment frame is likely to have ductile beam hinging. A non-linear behavior at the elemental level, but leading to a predictable global response. Variation in elemental level behavior is likely to lead to proportional variation in global behavior.

By contrast a poorly designed older moment frame may have a multiple possible failure mechanisms, some of which may result in sudden failures – for instance column shear failure. This leads to step-change structural responses and unpredictable building behavior.

This unpredictability in older buildings, can be seen as them having a disproportionate response to a small selection of structural elements. Our challenge as practicing engineers is how we address this unpredictability in an assessment.

A Real World Laboratory

Beca have had the opportunity to tackle this issue in practice on a number of recent seismic assessments. We have recently assessed a number of comparable 1950 through 1960 reinforced concrete moment frame buildings, all of which show a sensitivity to the behavior of relatively few structural elements, and where information about those elements is somewhat unreliable.

In particular, we have recently undertaken an independent assessment of a large institutional, RC moment frame building, which had previously been reviewed by another engineering consultancy. The original assessment had followed a Non Linear Time History Analysis (NLTHA) approach, where-as the Beca assessment utilized a Simple Lateral Mechanism Analysis (SLaMA) approach. This gave us an excellent opportunity to evaluation the two forms of analysis side-by-side and review their relative attributes when used in practice.

We would stress that the original NLTHA was undertaken by a reputable consultancy and by capable and competent engineers and in our opinion their use of it on this case study project represents good industry practice for NLTHA. Where NLTHA is critiqued in this paper, we consider it to be in relation to inherent weaknesses in the analysis method, even when used carefully by a capable practitioner.

The Building

The case study building is a seven story moment frame built in 1960. It is a high importance level building in a relatively low seismicity zone. The building is split in two by a full height seismic joint in the middle. For the purposes of this paper we will discuss the smaller of the two halves of the building as it is the simpler structure and thus more clearly demonstrates the issues involved.

The building was found to have a number of structural weaknesses, the most significant of which were:

- Adverse effects of concrete infill walls leading to early failure of the main frame.
- Understrength joints with potentially undesirable failure mechanisms.

Both of these will be discussed below, in particular how the analysis method effects the inherent understanding of each issue. For brevity, other structural issues with the building will not be discussed.

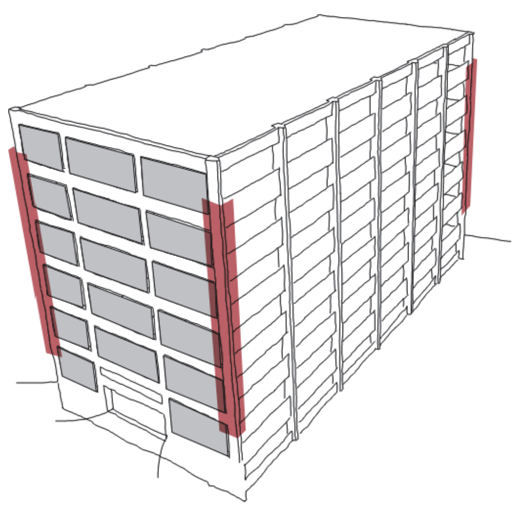

Figure 3. General form of the smaller building. Critical columns are highlighted red and infill walls in grey

Infill Walls

The endmost transverse frame of the building had been infilled (at the time of construction) with thin reinforced concrete walls. These infill walls formed part of the cladding system of the building. The infill walls were fixed along their bottom edge to RC frames. Around the sides and top the walls had been constructed by placing a piece of plasterboard against the RC frames, and then casting the infill wall against this plasterboard.

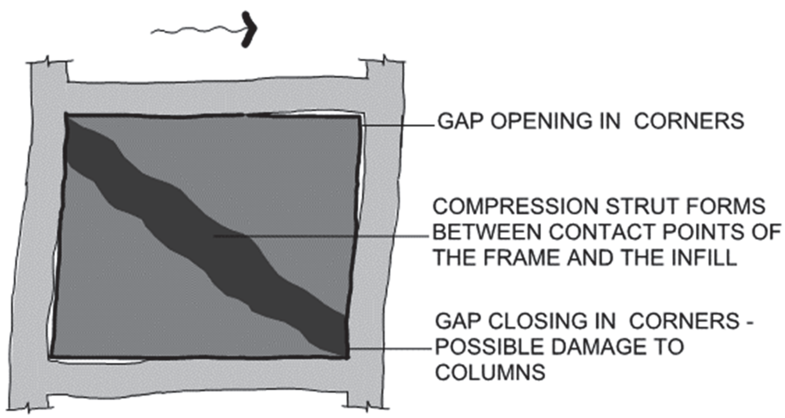

Figure 4. Infill wall subsystem. Note criticality of size of gap.

The plasterboard appeared to be deliberately placed with the intention of forming a seismic gap (and had been similarly used in other locations on the building for similar purposes). However, both Beca and the original assessors considered it highly unreliable as a gap element, with a range of possible effective gap sizes between 0mm and about 20mm depending on:

- Original thickness of plasterboard
- Compressibility of plasterboard
- Possibility of either air gaps or direct concrete bearing from construction inconsistencies.

If the gap was 0mm, then the infill walls would strut between RC frame joints, leading to a likely column shear failure mechanism and likely loss of gravity load carrying capacity. Moreover, the stiffness of the end frame with fully strutted walls, compared to the other frames, meant that a very high proportion of the load went to this end frame, leading to a much earlier failure point and much lower *%NBS*.

By contrast if the gap was 20mm, this was broadly similar to the drifts at which the general RC frame joints were starting to govern building behavior, so the effect of the infill walls because minimal and the building could be considered to have a significantly higher *%NBS*.

The likely gap behavior was somewhere within this 0mm to 20mm range. But where? We were faced with the unusual situation where the building behavior was significantly influenced by the compressibility of some plasterboard.

The Impact of the Analysis on Thought Processes and Reporting.

Both the SLaMA analysis and the NLTHA analysis picked up the issues of the infill walls, and of the plasterboard. However, nature of the analysis leads to inherently different thought processes being required, and thus a different emphasis being put on the conclusions and reporting.

The SLaMA assessment, by its nature, requires the determination of failure hierarchies, and links individual failure hierarchies to the overall building behavior in a very direct and simple way. This means that when viewing and considering the outcomes the impact of the infill wall gap was directly linked to the overall building behavior. There was a direct and visible correlation between the gap size and the *%NBS* that we would finally be advising. We were therefore acutely aware of the uncertainty related to this gap – which largely depended on the characteristics and condition of 60 year old plasterboard. This lead directly to us heavily emphasizing the high uncertainty associated with this assessment in our reporting and conversations with the client.

The NLTHA by comparison, requires the gap to be inputted as part of a much larger model. While the gap can (and was) assessed using sensitivity analysis, the NLTHA assessment loses much of the clarity of causation. This lack of clarity became especially important as the assumed gap size increased and other structural elements came to influence the system behavior.

Because those using a NLTHA are obliged to make many (and often complex) assumptions at the beginning, and because clear linkages from the assumption to the outcomes are not often visible in a highly complex system such as a building, it can be extremely difficult to tease out the criticality of the various assumptions at the end of a NLTHA. This difficulty exists even when ample time for careful consideration is available. Within the time constraints of commercial practice, these difficulties can be severe.

The Beam-Column Failure Hierarchy

The other significant structural behavior in the building is the beam to column to beam-column-joint hierarchy. For this building, the three capacities of each of these three components, and of both shear and bending failures for each component are all relatively similar, without the obvious and consistent hierarchy expected in a new building. Further, the reinforcing ratios vary per level, meaning there is not necessarily consistency of hierarchy over the levels.

There are also a number of unknowns (and unknowables) associated with it being an existing building. Although reasonably good drawings were available, information on material properties all had to be assumed. Most notably concrete strengths were not reliably known, which in turn influenced shear capacity, and thus influenced which failure mechanism governed.

Although the available drawings showed laps locations, stirrup spacing and the like, and these had been verified with intrusive investigations at selected locations, there is still no practical way of considering the many tweaks, adjustments, and permutations that inevitably eventuate on site. To give one example, the smaller half of the building contains round bars, while the large half of the building contains deformed bars, despite only being built one year later. Such a detailing change can have a direct and dominant impact on beam-column failure hierarchies and thus on the overall displacement compatibility of the building.

Figure 5. Deformed bar used in half of the building, and round bar being used in the other half.

Impact of Analysis on Expected Extent of Structural Issues

When the uncertainty around the beam-column failure hierarchy is filtered through different analysis techniques, the outcomes can be quite different.

The NLTHA analysis showed frame failures occurring in some bays at one of the upper levels at approximately 25%-30% NBS. The analysis also identified that shear strengthening of columns in this area would also likely be required.

The SLaMA analysis showed similar frame failures occurring at one of the upper levels. However, because there was high visibility of the relative capacity of *all* the beams, columns and joints, it also made very clear that many of the other frames and other levels were also likely to have similarly low capacity.

This difference in transparency for non-critical members made a significant difference in understanding over extent of the structural issues and likely strengthening costs and disruption. This is despite the fact that the *%NBS* score was similar from both methods.

While the NLTHA did not directly suggest than non-critical members had adequate capacity, neither did it clearly show that they had relatively low capacity. Instead the failures of the most critical members suppressed visible failures in non-critical members.

The SLaMA analysis by contrast, showed very clearly that non-critical members were only a relatively small margin away from becoming critical. Again this could be directly compared to the relative uncertain of the initial assumptions, and it could easily be determined that the differences were within the margin of error of the initial assumptions.

Time and Other Practicalities

While the above has focused on the additional clarity that can be provided by a SLaMA type analysis, there is another, more prosaic advantage: Time required.

The SLaMA analysis is a fundamentally simpler, more straightforward approach. This means that for most practitioners it can be applied far more swiftly than NLTHA. Moreover, information about the building being assessed may be uncovered in a stepwise manner. Initial crude assessment can give a very rapid early indication of likely building behavior, and subsequent analysis steps can be adjusted to suit the finding of early stages. By contrast, NLTHA is reliant on a fully functional analysis model being developed and validated before reliable initial outputs are available.

SLaMA also has the advantage of being able to be implemented by most engineers. In a market like New Zealand where the use of NLTHA is not widespread, these means that SLaMA can be used as a consistent approach by the majority of practitioners.

The Path through the Woods

It is the authors' view, based on our experience with the practical application of the New Zealand Seismic Assessment Guidelines, that SLaMA offers an enhanced assessment method over more computationally intensive methodologies such as NLTHA.

We consider that there are practical advantages to time and cost. Most importantly we consider there is a significantly enhanced ability to understand the full range of likely building behaviors, and significantly better ability to comprehend the impacts of uncertainties on the assessment.

We would make the analogy to finding a path through the woods. The route through the structural analysis of a building is complex, and on the journey the engineer is faced with many decisions and many possible forks in the road. Complex analysis take all of those forks and decisions and combine them together in a largely opaque manner. The engineer is left to trust that the individual decisions were correct and to wait and see just where they will pop out of the forest, all the while knowing that many of the decisions made are inherently inaccurate.

SLaMA by contrast forces the assessment down to its simplest component. Driving the engineering equivalent of high level decision between taking the high road or the low road through the forest. While it lacks the precision of computational analysis, it offer the very important advantage of allowing an engineer to see the woods, despite the trees.

References

MBIE, 2017, *The Seismic Assessment of Existing Buildings, Technical Guidelines for Engineering Assessments*, The New Zealand Government. (can be downloaded from www.EQ-Assess.org.nz)