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Thinking outside the (black) box: A holistic approach to complex analyses

A.G. Cattanach, R.H. Ballagh & O. Al-Gailani
Dunning Thornton Consultants, Wellington, New Zealand.

ABSTRACT

As our tools continue to grow in power, our ambitions draw us to attempt to more accurately predict our structures' performance with more complex analyses. While some phenomena can only be accurately predicted by these analyses, we do not always obey the principle of Occam's razor, or the (miss) quote of Einstein that "everything should be made as simple as possible and no simpler". Like coding, a complete analysis can be bunk just because of one incorrect entry. As such, parallel simplified analyses and benchmarking against precedent provides a robust framework to check ones' complex analysis as it unfolds.

This paper suggests a framework that can surround complex analyses, some classic stumbling blocks, and the tools to overcome these. Borne out of Peer Review experience observing many different practitioner's styles this paper attempts to capture a useful approach for both designers and reviewers. Examples of the writers' own projects will be used to illustrate the approach in practice.

1 INTRODUCTION

As we are human, our inclination can be to do the good bit first - dessert before dinner and the like. With complex modelling, the most immediately rewarding part is building up the model and seeing it displayed in front of you. Through bitter experience we have found that this is the tip of the iceberg for the detailed proofing work that needs to go on behind the scenes after the initial model is built, to ensure it works correctly.

Complex models often only need one minor detail to be incorrect to cause major inaccuracies in the output. Through proofing our own models, cross reviewing others' models in our own office, and peer reviewing many projects over the years, we have found that a more disciplined approach is important to achieving good results.

This paper offers one recipe for how to eat your meat before your pudding (Pink Floyd 1979). It is based on building up slowly from simple to the complex and back-checking at each step.

2 BASIC ANALYSIS

Whilst some may dismiss them as old-school, hand calculations are an important filter: complex problems need to be thought through in detail to enable them to be distilled down to very simple analogies. When you consider the amazing structures across the world that were created in the days of nothing but hand calculations, it is a little sobering to wonder if we've made significant progress. Most experienced engineers in our experience would believe they could understand a problem to within 20-30% by such simplified analyses. As such, these are the most important order-of-magnitude error detectors throughout the whole process.

In normal practice, using hand calculations for early phases of designs it is normal to limit analyses to basic methods due to cost and time constraints. In a similar manner, approximate hand calculations should be carried out before any complex analyses for both new and existing structures.

3 SIMPLIFIED ANALYSES

The diagram below outlines steps one can take from simple to more complex analyses. These are common structural modelling methods below the level of the non-linear problems this paper is aimed at. However, for any large or complicated building, moving upwards through these steps does not take particularly long and gives one a deeper and more focused understanding of each part of the building as you progress.

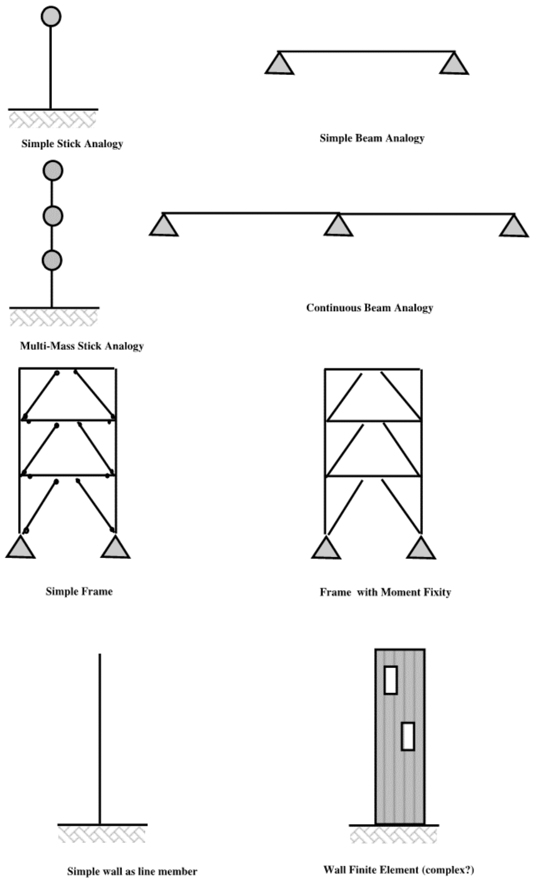

Figure 1: Example types of simplified structural analysis in order of complexity

The secondary benefit of linear models is that the structures are at equilibrium. They can be used to back-check the distributions of shears and moments coming out of later complex non-linear models, when the engineer can become swamped with data and envelopes or maxima of results are resorted to.

The process of running through these more prosaic steps can show unintended modelling issues. Qualitative assessment of bending moment and shear force diagrams can visually diagnose misplaced pins or support reactions. Developing engineers must practice the art of drawing any bending moment diagram shapes to approximate scale without numbers: we suggest developing this instinct is an essential part of being both an accurate and a creative engineer.

Always check equilibrium and summarise.

4 SENSITIVITY CHECKS

Unfortunately, we do not ever get the pleasure of analysing regular new structures floating in the air or on infinitely hard rock. When modelling more unknown materials, such as soils, existing building elements, and even new concrete (appropriately representing cracking), there is not just one result.

It is important to understand the effects that varying these parameters have on the model. For example, the common geotechnical practice of doubling and halving soil spring parameters will quickly tell you whether the deflection is sensitive to the structural stiffness or the interaction with the ground.

This is most easily done in the simplified environment, as models can be quickly re-run, fewer results are produced, and the range of behaviour expected can be mapped while still retaining equilibrium.

The fundamental reason to do parametric analysis is to understand how changing one part of the behaviour may change the entire assumed mechanism, and therefore how the building may perform (or fail). Again, it is far easier to explore this when only having to check a few results rather than being swamped in a large data management exercise. This is illustrated in the example below.

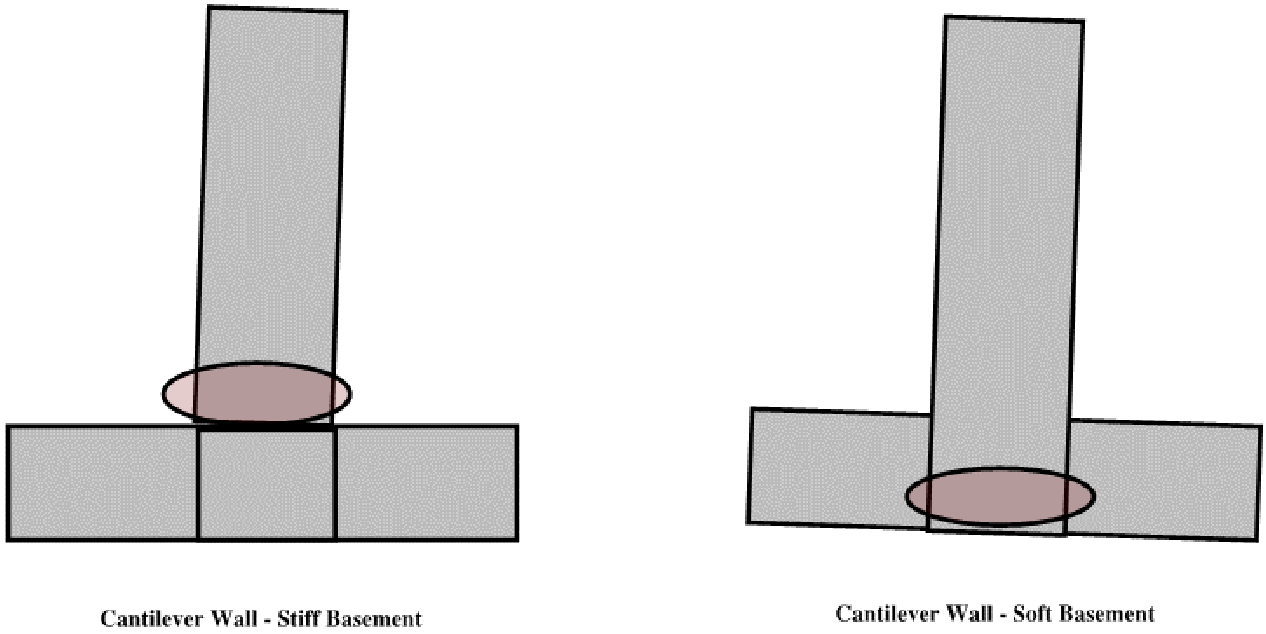

Figure 2: How changing soil parameters can affect the structural mechanism

Having experimented with changing these parameters, you will then be able to determine whether their variance can be linearly extrapolated (i.e. these simplified analyses are enough) or if multiple complex analyses need to be carried out. This is discussed further, later in the paper.

5 UNDERSTANDING THE NON-LINEAR ELEMENTS THAT YOU USE

It has been our experience that while in theory one can understand how an element works from the textbook or manual of the program, it is only by placing an element in a model and applying loads that some of the idiosyncrasies become apparent. Yet again, the best way to do this is with a very simple model.

It is important to understand how the non-linearities interact. Geometric non-linearities shift equilibrium in complex ways. Time steps affect how accurately results converge. Misrepresenting damping can make forces disappear entirely. Below is a list of some common mistakes we and others have commonly made:

- Using Rayleigh damping, and loosing forces where frequency is higher than the range specified, especially when using gap or hook elements
- Correct end fixity and transference of shears or axial forces to each end in complex links.
- Accidental additional restraints
- Locations where members, restraint springs or links have been entered twice between two nodes.
- Matching damping to the analysis type, including inputting effective damping for static analysis to set up the initial stiffness matrix correctly for certain types of analysis.
- Getting timestep interval and damping right when using gap or hook elements that have large changes in stiffness when they contact

Our recommendation is that when using any complex element for the first (or second) time or in a way you haven't used it before, apply forces or displacements to it in the order of what you might expect in the main model. This always takes less time than you think. To use the figure of speech "searching for a needle in a haystack: a complex model is an exponentially larger haystack.

6 EXPECTED RESULT

Now that all the hard work is done, you understand the building pretty well and have an estimate of your expected results. These key performance parameters should be summarised: an example list would be as follows:

- Backbone curve of the pushover of the building in each direction
- Expected storey displacements
- Expected storey accelerations
- Expected additional corner displacement/torsional sensitivity
- A few critical member or connection forces
- Base shear equilibrium, including centre of resistance

7 COMPLEX ANALYSIS

Much has been published at these conferences regarding complex analyses, e.g. Oliver et al 2012, and many of the material parameters are captured in the 2017 NZSEE Assessment Guidelines.

The intent of what is being suggested here is to minimise the amount of data that needs to be sifted through. We have many tools nowadays to sort data, and it is relatively easily managed. However, it only tells us the **what**, whereas engineers what we are trying to establish is the **why**: the load path from cause to effect. To minimise the data output, where possible only a single model should be interrogated. As such, one's conclusions would be established as per the figure below.

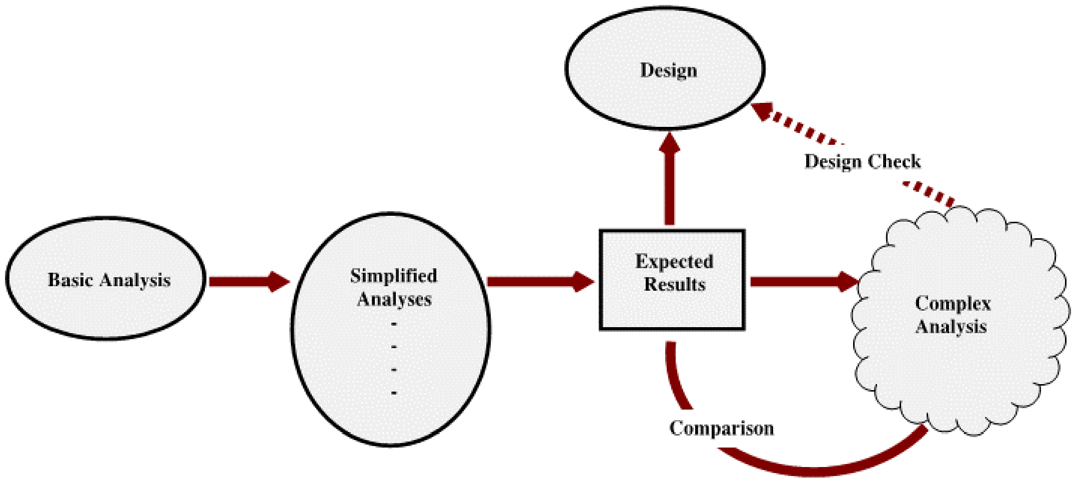

Figure 3: Diagram of analysis process: Low Sensitivity

Alternatively, if the sensitivity checks show that the non-linearity will exacerbate the variations in behaviour, it is possible that a second or at worst a third iteration would need to occur. This is shown in the figure below.

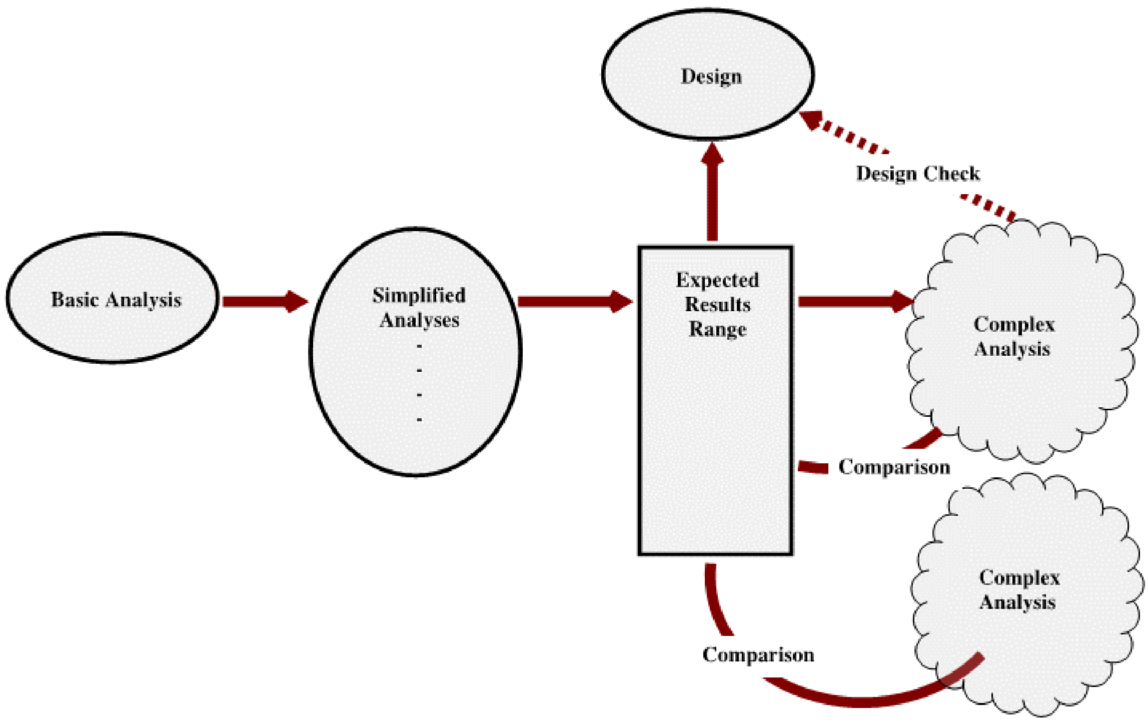

Figure 4: Diagram of analysis process: High Sensitivity

We suggest that if the variation in an unknown parameter causes a larger variation in a model due to its non-linearity, this is an inherently unstable system. As earthquake engineers, our most humbling understanding is that we know little about the magnitude and nature of earthquakes, and consequently if small variations and unknowns cause large variations in behaviour, the structure is unlikely to be robust.

A model is only an attempted model of reality, and caution must always be used in taking results at their face value.

8 EXAMPLES

8.1 Bowen Stage II

This project comprises two six-storey steel-frame buildings. Lateral load resistance comes from nominally elastic braced frames in parallel with viscous dampers. This was the first large complex viscous-damped structure we had analysed, and hence a very conservative stepping-through of the process was undertaken.

8.1.1 Basic analysis

Hand calculations using displacement-based design and a target level of damping set by precedent.

8.1.2 Simplified analysis

Our first analyses were a single degree of freedom computer model, running four types of analysis: static, modal, sinusoidal, then earthquake time histories through a single non-linear link element. This simplified analysis could be easily modified to investigate the benefits of different levels of damping, could be easily correlated with the hand calculations in the basic analysis above.

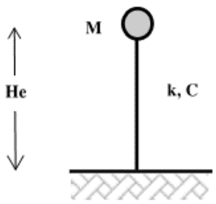

Figure 5: Single degree of freedom analysis

Our second analyses used two link elements, rigidly joined, separating the damping and the stiffness parameters. The first analyses are repeated, and the expected transfer of forces between damper elements and stiffness elements could be understood both as an absolute and at various key points during the earthquake records.

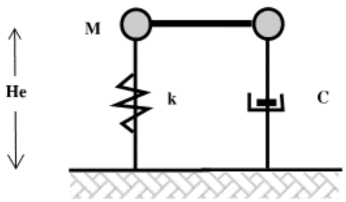

Figure 6: Two degree of freedom analysis

We then investigated over the height of the building in a 2D frame analysis as shown below. Again, the four types of loading are applied starting from static and working up to time histories so that results can be benchmarked back to the first and second analyses.

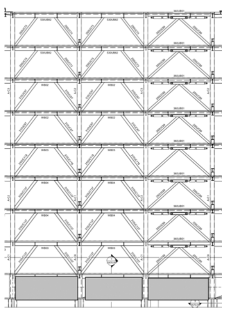

Figure 7: 2D simple, then 2D complex analysis

The 2D analysis was much simpler to run than any 3D model and so we used this to vary the distribution of damping up the height of the building. For this project, we used minimising floor acceleration as the target to optimise. Our first model used a vertical distribution based on precedent and the commonly available commercial unit sizes. It was interesting that all other options considered provided worse floor acceleration performance. For uniform buildings such as these, I suggest this is again an example of where trying to reinvent the wheel from first principles may be unnecessary.

Once the damper distribution was settled, member and connection checks could be made. Most importantly, the centre of mass deflection and acceleration results can be correlated back with the previous basic and simplified analyses. An estimate of the likely higher mode actions (the dynamic magnification) could be benchmarked against analogous rules in conventional structural steel or reinforced concrete codes.

8.1.3 Final Complex Analysis:

By this time, full 3D analysis was carried out simply to check torsion (and hence frame displacements) were within what was predicted from the previous analyses. As such, all designs could be completed with the 2D models and save wading through the excessive data that comes from a 3D analysis.

8.2 Base isolation: equilibrium above and below an isolator

We have encountered issues in the detailed modelling of base-isolator units in our own and others' analyses in many instances. Key issues have been:

- Appropriately resolving P-delta forces and distributing them appropriately above and below the bearing
- Placing the centre of shear for the isolator at the correct height relative to the structures above and below the isolator plane
- Not adding (5%) background damping to the main isolator modes
- Imposing appropriate axial loads to friction-based devices, especially when these vary due to oscillation of the superstructure

The (draft) NZ base isolation guidelines due to be issued immanently require equilibrium to be explicitly solved at the isolator unit, that will typically require hand-calculation checks as well as data from the modelling. Care should always be taken with these essential elements, especially with regard to axial loads.

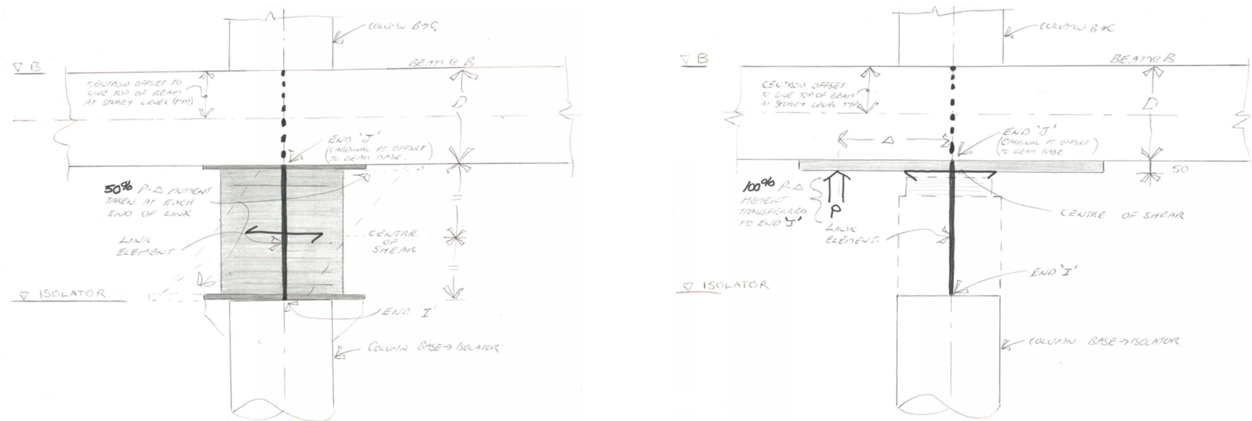

Figure 8: Diagrams used in 2004 Wellington Hospital design process to clarify how isolator units were to be modelled

8.3 Base isolation: impact with the “rattle space”

For two recent Dunning Thornton projects involving base isolation, we selected a design where the isolator travel was greater than the available rattle space. This was done to ensure that an additional force resistance was applied to the building at extreme displacements before the travel of the bearings was exceeded. Gap elements to model the impact of the building against the rattle space impose very high-force short-period energy into the building, which is extremely difficult to capture mathematically. Using ETABs, and therefore Raleigh damping, it is easy for short-period forces to disappear through over-damping. To understand this better, we employed two techniques. One, using a single-stick model only to represent the building, and therefore have no higher mode elements. Two, to pre-model an impacting mass and look at how the energy was absorbed and the accelerations transmitted using only two degrees of freedom. The focus of this analysis was to properly understand how much the building’s maximum displacement was reduced. As such it was essential that we didn’t add complexity which could cause the model to be inaccurate through over-damping. Consideration of the resulting forces could be done in a secondary manner based on spectra or acceleration histories on the few masses involved, avoiding issues with Rayleigh damping. The model is illustrated in the figure below.

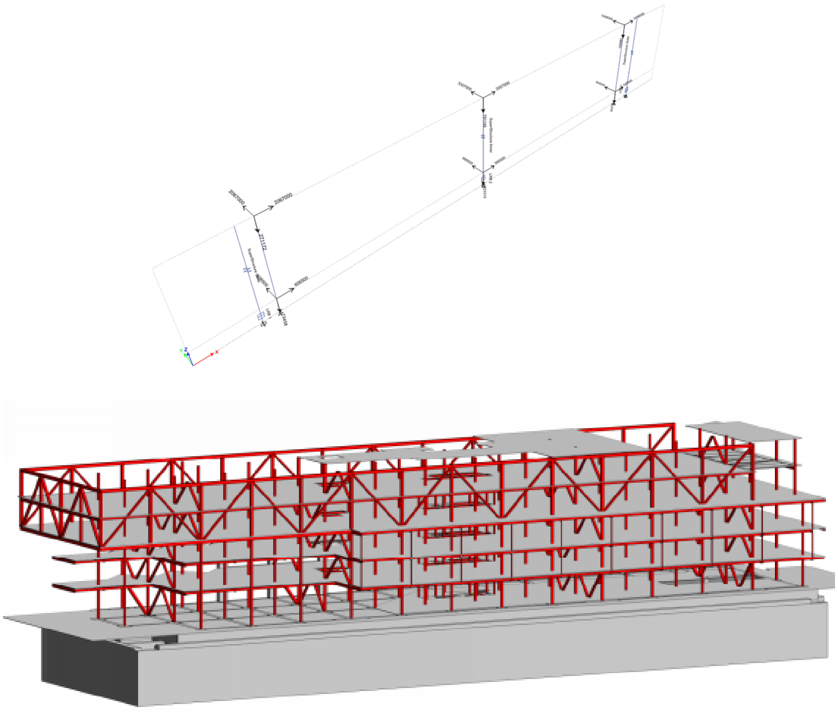

Figure 9: Simplified model targeted to investigate impacting the rattle space only, vs total building

9 CONCLUSION

Analysis is only as good as the theory and execution it is built on. Complex models only need one unintentionally or unknowingly misplaced parameter to render some or all of the results as bunk.

The methodology suggested here is a way of building up your understanding of the building slowly, embarking on more and more complex models step by step. The most important part of this is to back-benchmark each step with your basic analysis before going forward into more complexity. Complex models are extremely useful, if correct, in understanding complex phenomena. It is my experience that in managing large amounts of output data the engineer spends a lot of time trying to distil down the critical aspects of "what" from the results, using up time that should be spent thinking about the "why". Good engineering is understanding the why, the load path, rather than just the what.

Resilient systems have redundancy for if something goes wrong. Resilient analysis uses more than one technique to try and check the same hypothesis. We have found many large errors in our own and others' work by using only simple methodologies. If engineers make standard the process of always benchmarking their complex models against these simplified analyses, as is proposed by this paper, we can not only strive for more accuracy but have the confidence to continue to extend the complexity of our representations of buildings without separating ourselves from reality.

10 REFERENCES

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Oliver, S.J; Boys A.G.; Marriott D.J. 2012 NZSEE Conference Paper "Nonlinear Analysis Acceptance Criteria for the Seismic Performance of Existing Reinforced Concrete Buildings

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