Performance Based Seismic Design Using NLTHA: Retrofit of a 1980s Twelve Storey RC structure in Wellington for New Seismic Hazard

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ABSTRACT

A Detailed Seismic Assessment (DSA) of a 12-storey Reinforced Concrete structure from the 1980s with precast hollow-core floors in the Wellington CBD revealed that the building's seismic rating was 35% of the New Building Standard (NBS), just above the threshold for being considered "earthquake prone." Key issues contributing to this rating include the seating capacity of the hollow-core diaphragm, inter-story drifts nearing the code limit, and the insufficient shear strength in the longitudinal direction due to unaccounted slab reinforcements which could lead to potential column shear failure. The seismic risk was further heightened by the new national seismic hazard model, which increased the seismic hazard in Wellington by up to 90% at this building's location. To address these challenges and future-proof the building, the owners decided to retrofit it to 80% of the new seismic hazard, which sets it at 150% NBS for the current hazard. The retrofitting strategy involved a combined approach of using viscous dampers along with some conventional strengthening which offered an efficient and sustainable solution. A smart framework of Performance-Based Seismic Design using inelastic time history analysis is used for the design. The paper outlines this design approach and its outcomes.

1 INTRODUCTION

With the growing focus on climate change and the pressing need to minimize the carbon footprint of any construction activities has led to a demand for a more sustainable structural design. As per the report of 2019 by the World Green Building Council, the world is in a state of climate emergency. The built environment and its associated activities cause 39% of the world's total carbon emissions.

Out of this, 11% of the global emission is attributed to *embodied carbon.* Embodied carbon is the carbon emission during manufacturing, transporting, constructing and end of life phases of the built environment. The report notes that this proportion of carbon emission will increase and may reach up to 50% of the carbon footprint of new construction by 2050. This aspect calls for a paradigm shift in the focus of our built infrastructure, from new buildings to retrofitting and retaining the existing infrastructure so that the *embodied carbon* contribution is minimized; in other words, minimize new building and demolition of existing structures and divert the resources to enhancing our existing infrastructure. Considerable efforts are already in place in this direction where minimizing upfront and embodied carbon is the primary focus.

1.1 "SEISMIC ISSUE" IN SUSTAINABILITY

A major impediment to such a shift in "focus" is caused by earthquakes. Most of the efforts in minimizing upfront carbon and embodied carbon are centered in the "non-seismic" part of the world, the methodologies developed there are not directly applicable to "seismic" regions mainly because these methodologies do not explicitly acknowledge the significance of "seismic resilience". In other words, solely focusing on minimization of embodied carbon without sufficient consideration of seismic resilience does not fulfil the goals of sustainability. Let's have a review of what we mean by the previous statement by examining the current practice prevalent in seismic engineering.

The conventional or classical ductile-design strategy relies on the structure absorbing seismic energy in a major earthquake by enduring large inelastic deformations. The inelastic deformations result in heavy economic losses in the form of material damage to structural and non-structural elements. Recent earthquakes, Christchurch 2011, Tohoku 2011, Kaikoura 2016, Kumamoto 2016, all have resulted in heavy damage to buildings and infrastructure. The loss incurred in the Christchurch earthquakes was more than NZD $ 45 billion, or about 20% of New Zealand's GDP. Similar observations could be made of past earthquakes as well. The 1994 Northridge earthquake resulted in a loss of ~US $ 44 billion. One of the major consequences of this level of damage is that it results in extensive demolition and re-building of the built environment. After the Christchurch earthquakes of 2011, ~70% of the central business district buildings were demolished. This obviously has a huge environmental impact. The adverse effects caused by these sorts of events in the environment are almost unfathomable and unsustainable.

The motto of minimizing embodied carbon and fulfilling the global need to mitigate the climate emergency, in seismic regions, demands a completely different design approach which is more than what is currently being done in "non-seismic" regions, mainly because the "seismic resilience" also comes into the equation of sustainability. Minimizing embodied carbon and increasing seismic resilience are in fact competing objectives. So, when sustainability must be implemented in seismic regions, the primary question to ask is how can we avoid what has happened in Christchurch, where ~70% CBD buildings had to be demolished? How do we ensure seismic resilience of our existing built environment?

The simple answer to this question is to retrofit the existing structures to survive and incur minimum damage. One of the successful and proven ways to reduce damage and increase resilience of existing buildings is by applying viscous dampers to control the structural response in an earthquake. In this paper, we discuss an application of viscous dampers to an existing twelve storey structure constructed in the 1980s which is retrofitted for the new seismic hazard.

2 VISCOUS DAMPERS- A MEANS TO INCREASE SEISMIC RESILIENCE OF EXISTING BUILDINGS IN HIGH SEISMIC REGIONS

Properly designed viscous dampers are highly efficient in reducing the effect of earthquake shaking on buildings in high seismic regions.

A fluid viscous damper is a fluid-mechanical device which induces forces proportional to the velocity. These velocities in a structure are out of phase with the structures displacements and accelerations. A typical section of a viscous damper is shown in Figure 1.

Fluid viscous dampers are a well-tested and dependable technology in this regard. They provide actions which are out of phase to the other structural actions and as a result minimize structural response to seismic loading. *If properly designed*, they minimize both drift and absolute floor acceleration. Consequently, they can reduce "downtime" and "damage" considerably and, *if properly designed*, ensure seismic resilience and continued operability during and after a major seismic event. Additionally, *if properly designed*, they require much less foundation intervention compared to other retrofitting technologies, such as "base isolation" systems (when the latter solution is applicable). Retrofitting existing buildings with base isolators is an expensive business, because of the extensive underpinning and foundation works which are usually required. Now the question that arises is what do we really mean by "*if properly designed*"?

Figure 1: A typical cross section of a viscous damper (Taylor Devices inc.) and an assembled unit (Taylor Devices inc.)

Before delving into that lets first look at the mechanics of viscous damper incorporated structure.

2.1 MATHEMATICAL MODELLING OF VISCOUS DAMPERS

The equation of motion incorporating the viscous dampers is:

$$\boldsymbol{M\ddot{u}(t)} + \boldsymbol{C_{structure}\dot{u}(t)} + \boldsymbol{f_{damper}(t)} + \boldsymbol{f_{NL}(t)} = -\boldsymbol{MI}\ddot{u}_g\boldsymbol{(t)} \quad (1)$$

where:

$\boldsymbol{M}$ represents the mass of the system,

$\boldsymbol{C_{structure}}$ represents the inherent damping in the system,

I represents the influence vector relating ground displacement to system displacement,

$\boldsymbol{f_{damper}}$ is the vector of forces in the structure due to the dampers, and

$\boldsymbol{f_{NL}}$ is the vector of nonlinear restoring forces in the structure.

$\boldsymbol{\ddot{u}(t)}, \boldsymbol{\dot{u}(t)}$ are the relative accelerations and velocities of the system and $\ddot{u}_g\boldsymbol{(t)}$ is the ground acceleration.

Depending on how $\boldsymbol{f_{damper}}$ is represented in the analytical formulation, the viscously damped system may be analytically classified as either a pure-viscous system or as a Maxwell system.

2.2 Pure Viscous damping

Figure 2 shows a nonlinear viscous damper modelled as a pure dashpot mechanism.

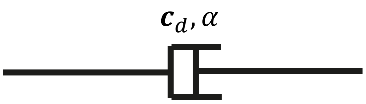

Figure 2: A viscous damper with "pure-viscous" modelling

When dampers are modelled as viscous, the equation of motion in Eq. 1 becomes:

$$\boldsymbol{M\ddot{u}(t)} + \boldsymbol{C_{structure}\dot{u}(t)} + \boldsymbol{C_d\dot{u}(t)^{\alpha}} + \boldsymbol{f_{NL}(t)} = -\boldsymbol{MI}\ddot{u}_g\boldsymbol{(t)} \quad (2)$$

Note that, if α is not equal 1.0 Equation 2 represents a system with both structural and damping nonlinearity.

2.3 Maxwell damping

A more realistic modelling of a viscously damped system uses a Maxwell model (Figure 3) in which the flexibility within the damper plus that of its supporting structure is represented explicitly.

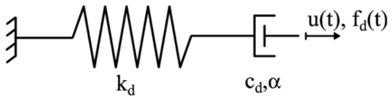

Figure 3: A Maxwell model of a viscous damper

A spring is in series with the dashpot which has a pure-viscous behaviour. This model is more difficult computationally as the spring and dashpot are in series, so, the force in the spring and dashpot are the same. The relative displacement and velocity across the model are the sum of the displacements and velocities of the dashpot and the spring, but the dashpot has no inherent stiffness and so the distribution of displacement in the spring and dashpot is not explicitly defined. This distribution must be resolved by iteration or by some other solution approximation.

With the Maxwell model incorporated, Eq. 1 becomes:

$$\left.\begin{aligned} \boldsymbol{M\ddot{u}(t)} + \boldsymbol{C_{structure}\dot{u}(t)} + \boldsymbol{f_{damper}(t)} + \boldsymbol{f_{NL}(t)} = -\boldsymbol{MI}\ddot{u}_g\boldsymbol{(t)} \\ \boldsymbol{\dot{f}_{damper}(t)} = \boldsymbol{\Psi(\dot{u}(t), k_d, c_d, \alpha)} \end{aligned}\right\} \qquad (3)$$

In a normal time-history analysis for seismic engineering, the semi-discretized equations given in Equations 2 and 3 are temporally discretized and solved using implicit integration schemes.

Typically, the “proper design” of a viscous damper incorporated structure adopts the Performance Based Design (ASCE41/FEMA P58) using nonlinear time history analyses. This involves subjecting the proposed design to a suite of ground motions (usually 11 Bi-directional ground motions) and establishing that it satisfies the relevant compliance requirements and target performance criteria. Variations in material properties also need to be factored into the design.

The standard industry approach is to extrapolate the simplified design approaches normally used for conventional structures to those incorporating viscous dampers. This results in an initial starting point. From there, we have observed engineers reverting to an intensive "brute force" process, where multiple analyses (in the range of 1000s) are conducted to refine the system. This involves varying damper locations and parameters in an effort to optimize the design. Depending on the building size and complexity, this iterative process can take months or even years to arrive at a compliant design.

Each iteration requires significant computational effort. For one intensity level, a single iteration involves 22 nonlinear time history analyses. Since there are usually at least three intensity levels (Serviceability, DBE, and MCE), each with specific performance requirements, this means that one iteration realistically entails 66 analyses, if all intensity levels are considered simultaneously. Depending on the building's complexities, multiple intensity levels may need to be considered simultaneously during the design process and hundreds to thousands of iterations may be necessary, making the process computationally intensive and extremely time-consuming.

As a consequence, we have observed engineers needing to terminate their efforts once they have achieved what they deem to be a compliant design as opposed to persisting in pursuit of an optimized design that consumes less material and achieves superior performance. The resulting designs tend to be material intensive, driving up cost and carbon emissions, while often falling short of achieving optimal performance.

Now why does this happen? The primary reason for this inefficiency lies in the "brute force" approach itself. In this method, engineers lack the ability to assess the complex load-sharing process that is crucial for determining the ideal placement and sizing of the dampers. Without a clear understanding of how loads are distributed across the system, it becomes nearly impossible to strategically quantify and position the dampers. This lack of insight leads to a more labor-intensive design process that ultimately falls short of optimizing performance.

3 A DESIGN PLATFORM FOR "PROPERLY DESIGNING" DYNAMIC SYSTEMS

To address these challenges and facilitate smooth commercially viable applications of Performance Based Design approaches (ASCE41/FEMA P58), a proprietary smart design platform called MOODD, based on advanced PBSD principles was developed. This platform produces design solutions explicitly accounting for these intricate physical interactions. By optimally tuning these "load sharing" interactions, the platform generates designs that not only enhance seismic resilience for a given cost, but also promote sustainability through reduced upfront carbon emissions. In addition to PBSD, the platform also has the capability to generate designs based on Performance Based Wind Design (PBWD) principles where the wind dynamic loading is considered which maybe applied for tall and super tall buildings. Two real life applications of the platform for retrofit for seismic loading are described below.

4 SEISMIC ISSUES

The structure presented consists of an existing 12-story reinforced concrete moment-resisting frame building from the 1980s, with precast hollow-core floors. The moment frames were well-designed and detailed for expected design level according to NZ 4203:1984 which is the predecessor of the current New Zealand code NZ 1170.5:2004.

A Detailed Seismic Assessment carried out by Beca rated the building to be at 35% NBS, which is just over the point where the building would be classed as "earthquake prone" according to NZ standards. The primary reason for this rating was due to the limited capacity hollow-core diaphragm and the frames exhibited calculated inter-story drifts close to the code limit of 2.5%. This resulted in all the seismic issues associated with hollow-core slabs which relate to loss of seating (where a unit slips away from its support), positive moment failure, negative moment failure and web splitting. Another issue was that, although the frames were well detailed, in the longitudinal direction of the building, the flexural overstrength of the beams did not account for the contribution of the slab reinforcements which resulted in creating a potential shear failure issue. All these identified issues resulted in the tenant moving out of the building, necessitating an immediate upgrading of the structure.

The seismic issue was further exacerbated by the release of the new national seismic hazard model by GNS Science (National Institute of Geological and Nuclear Sciences). The new hazard model accounted for the recent studies done on the Hikurangi subduction zone situated to the east of the North Island of New Zealand. This resulted in a greatly increased hazard for Wellington where it is increased by a factor of 1.5 to 2.0 depending on the site location. The specific site this building is on indicates an increase of 90% in the hazard.

The risk caused by the lowered seismic rating made the owners decide that retrofits needed to account for the future hazard increase. Though as per the direction of MBIE (Ministry of Business, Innovation and Employment) there was no need to consider the new hazard, it was still decided that for future-proofing, 80% of the new seismic hazard will be the target. This sets the target strengthening for the existing building at150% NBS.

To achieve this target of 150% NBS requires an almost a four-fold increase in the capacity required by the original 1984 building code. For conventional means of seismic strengthening, this would result in an enormous amount of intervention both in the foundations and in the superstructure even to achieve 70% NBS (~ twice the current rating of 35%). Along with the financially infeasible high cost for a 150% target strengthening retrofit, this intervention will also affect the functional and aesthetic aspects of the building making it untenable. Again, such a conventional scheme would result in very heavy damage and loss in a future code level earthquake as evidenced in similar buildings during past earthquakes. To make the whole anticipated commercial outcome attractive, a smart retrofit strategy was needed which would provide a much higher performance, less intervention, and the same or less cost compared to a conventional scheme.

5 RETROFIT CONCEPT AND PERFORMANCE BASED DESIGN

Viscous dampers were a natural choice for this purpose mainly because of the “out of phase nature” of the viscous forces with respect to the inertial and stiffness induced forces in the structure. Though viscous dampers possess this property, they must be “properly designed” to achieve the targeted performance within the set budget. It was almost impossible using the conventional design approaches of energy-based or displacement-based approaches to meet the objectives of this project. The client considered the project financially feasible only if 150% rating could be achieved at a budget which is less than the cost of conventional strengthening for a target of 70% NBS. MOODD, which is a Performance Based Seismic Design platform (ASCE 41-23) was chosen as the means to provide design to meet these challenges. The obtained design was then subjected through the NZ 1170.5:2004 alternative solution compliance pathway to demonstrate compliance.

Figure 4.0 shows the 3D analytical model of the 12 storey structure.

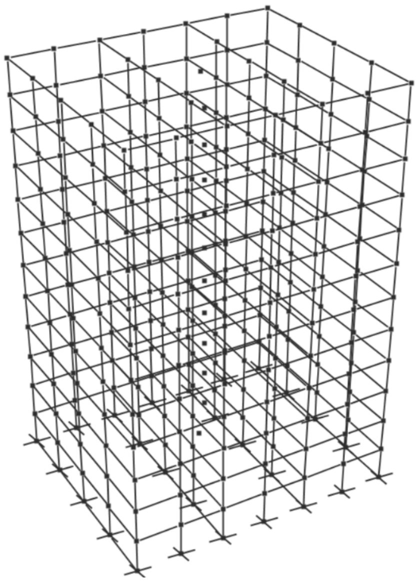

Figure 4: 3D model of the 12 storey RC structure.

Figure 5 shows the ADRS (Acceleration-Displacement Response spectrum) curve for the system. The drift of the uncontrolled (without dampers/original structure) was of the order of 9% in a MCE earthquake (blue line demand in figure 14) and of the order of 5% in the DBE earthquake (green line demand in figure 14). The target drift was chosen as <1% in DBE and <2.0% in MCE earthquakes to mitigate the hollow-core issues as per the recent experimental research guidance from SESOC (The Structural Engineering Society of New Zealand).

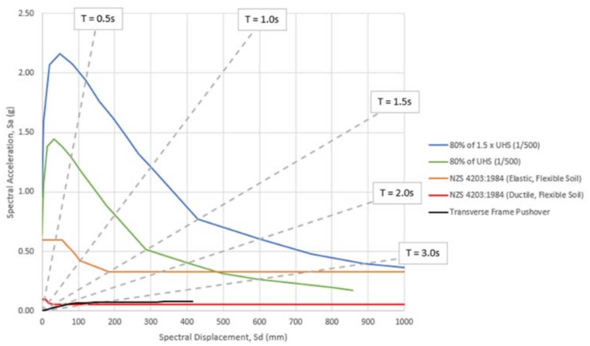

Figure 5: Acceleration-Displacement Response spectrum) curve for the case study structure

6 PERFORMANCE ACHIEVED

Figure 6 represents the drift plots for both longitudinal and transverse directions of the viscous damper incorporated building when subjected to multi-directional earthquakes. The maximum inter-story drift in a DBE earthquake is <0.8% and the maximum inter-story drift for a MCE earthquake is <1.8%. A 20% uncertainty is attached to the DBE drift targets and a 10% uncertainty is attached to the MCE drift targets.

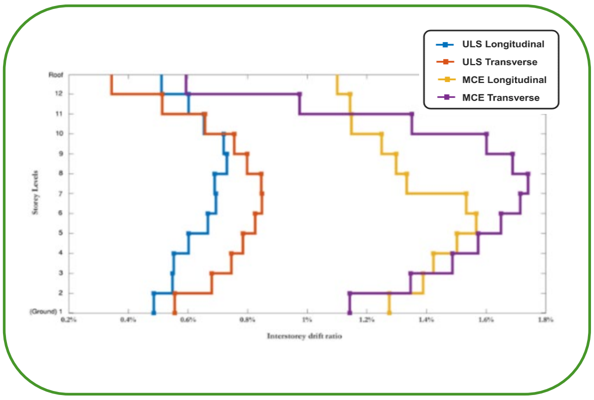

Figure 6: Inter-story drift plot of the damped structure

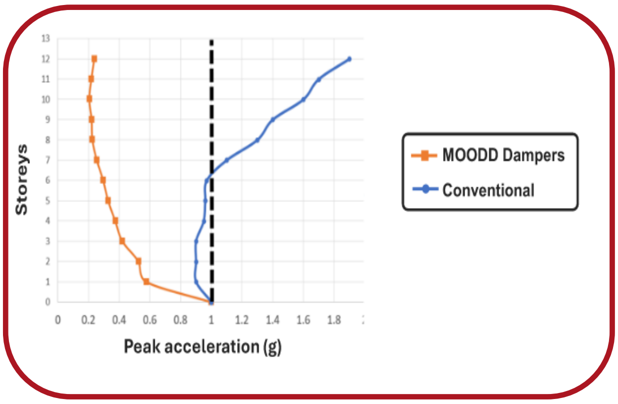

Figure 7: Comparative Floor acceleration plot

As shown in Figure 7, the comparison between traditional and PBSD designs using MOODD, results in significantly more sustainable solutions with minimal initial carbon footprint. The reduced floor accelerations as shown by the orange line results in significantly less on floor works. Moreover, the smartly designed viscous dampers negated the necessity for additional foundation work by effectively addressing net foundation retrofitting needs. Also the MOODD designs were done in such a way so that there was no need for additional foundation work.

7 CONCLUSIONS

The paper presents the retrofit of an existing twelve storey RC frame structure. It is shown that using MOODD-PBSD platform, it is possible to achieve highly sustainable and economic solutions. This innovative approach has proven highly successful in enabling cost-efficient seismic retrofitting of buildings with significant vulnerabilities (drift and acceleration related) in high seismic regions. The resultant retrofit solutions achieved a substantial reduction in total cost and embodied carbon compared to that possible using conventional analysis and design techniques and obviously even greater savings when compared to the alternative of the demolition and reconstruction of a replacement building.

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