TYPOLOGY-BASED SEISMIC ASSESSMENT: HOW TO ASSESS AN ENTIRE COUNTRY

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Abstract

Seismic assessment is typically undertaken on a small-scale, building-by-building, basis. This approach is prescribed in most international codes and guidelines. However, there is occasionally a need to undertake seismic assessment on a larger scale, whereby region or country-wide assessment is required. This requirement might be triggered by the emergence of induced earthquakes, changes in legislation or region-wide risk mitigation programmes. In these situations, involving tens to hundreds of thousands of buildings, traditional assessment techniques become limited in their ability to scale while maintaining quality and consistency. Conversely, macro region-wide assessments typically lack the ability to deliver building-specific outcomes.

In this paper, the underlying concepts of a system to undertake seismic assessment on a massive scale are presented. The system relies on a library of pre-assessed non-linear building capacities that are correlated to certain building characteristics. To ensure compliance with the relevant Standards, the capacities are determined probabilistically using outputs from traditional seismic assessments. A tiered approach is used, whereby varying levels of assessment scrutiny can be applied to building typologies depending on their relative vulnerabilities. In the first tier, only fundamental characteristics are required and consequently the results are more conservative; however, this enables compliance to be demonstrated for many buildings with low-vulnerability. For each successive assessment tier, more building characteristics are required, resulting in more accurate outcomes. If a building is deemed to comply at one tier, then no further assessment is required; however, if the building is not shown to comply then it proceeds to the next tier. This approach makes it possible to rapidly assess large numbers of buildings using only fundamental building features.

Where a building is encountered that cannot be defined by its features, it proceeds to a traditional seismic assessment using methods such as NLPO and NLKA to determine compliance. The use of these methods allows for building capacity to be decoupled from demand, which facilitates the flexibility to assess buildings of similar typology in regions of different seismicity. The results from each traditional assessment can be linked to the building's characteristics and entered back into the system. The system is therefore a learning system that increases in accuracy over time.

Where a building progresses through all assessment tiers and is found to be non-compliant, strengthening is required. The system has a library of pre-engineered seismic strengthening solutions that can be used to address the non-compliant building components. These solutions have capacities, costs and other non-price attributes associated with them, which allows an assessor to rapidly trial many different strengthening strategies to efficiently determine the optimum solution based on the stakeholder priorities.

The system is deployed within a web-based application, which ensures consistency across all building assessments and enables field-based assessments using mobile devices. The application also enables other features to be in-built, such as QA/QC, automated reporting, progress tracking and stakeholder communication.

Keywords: Seismic assessment; Seismic risk; Strengthening

1. Introduction

Seismic assessments are undertaken for a variety of reasons, such as safety, compliance with regulatory requirements, commercial drivers, etc. For these reasons, seismic assessment of buildings is typically undertaken on an individual basis. Where multiple building assessments are required, individual assessments are undertaken repeatedly. This process becomes limiting, and problematic, when large numbers of seismic assessments are required. Examples of when this situation might arise include the cases of induced seismicity in The United States and The Netherlands, as presented in Fig. 1 (a) and (b), respectively. Further examples include changes to legislation or attempts at region-wide seismic risk mitigation.

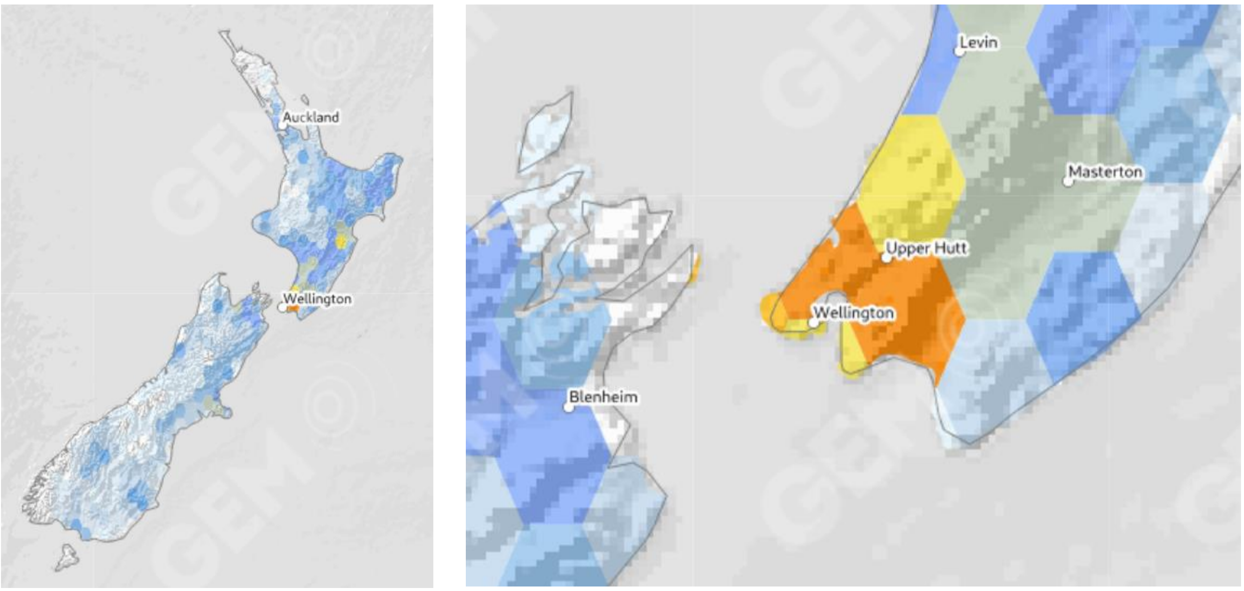
In these situations, the seismic hazard of a region may increase significantly over a short period of time, affecting a large population base and associated building stock. Buildings in the affected region need to be appraised to ensure compliance with the overarching safety philosophy, which is undertaken by way of seismic assessment. When undertaken in a traditional manner, the process of seismically assessing buildings on this scale may take decades. Some efficiencies can be gained through refinement of this process; however, it is difficult to achieve a step-change in efficiency due to the deterministic nature of traditional assessment processes. Furthermore, other factors such as maintaining the quality and consistency of assessment outcomes, become increasingly difficult. To increase the speed that the assessments can be undertaken, many different assessors are required, each with varying levels of proficiency and biases. Consequently, as traditional assessment techniques are scaled, quality processes become increasingly complex to maintain assessment consistency, which is a basic stakeholder expectation.

(a) Seismicity in Oklahoma, United States caused by wastewater disposal [1].

(b) Seismicity in Groningen, The Netherlands caused by natural gas extraction.

Fig. 1 – Examples of induced seismicity around the world.

Probabilistic approaches to seismic assessment address these issues of efficiency and speed; however, they are unable to produce the required building-specific outcomes. An example of this is the seismic risk across New Zealand, presented in Fig. 2 (a). Seismic risk in this instance is the amalgamation of seismic hazard, exposure and consequence. When viewed at a sufficiently high-level, such as countrywide, this probabilistic type of seismic assessment can give useful insights that might be used to inform strategic decisions, such as policymaking. However, as shown in Fig. 2 (b), which is a magnification of the same plot to show the Wellington region, when wanting to make region-wide decisions a probabilistic approach cannot produce the required granularity, particularly not to determine building-specific outcomes.



(a) New Zealand. (b) Wellington region.

Fig. 2 – Probabilistic seismic risk assessment [2].

To address these shortcomings, a new system is required to efficiently facilitate seismic assessment on a massive scale whilst produced building-specific outcomes. This paper presents a system that allows for rapid seismic assessment utilising a typology-based approach. The system provides efficient, reliable and consistent assessment outcomes.

2. Technical Basis

The optimised seismic assessment system (OSAS) has been developed by many technical consultants, with inputs and feedback from some of the top minds in earthquake engineering. The system relies on a series of 'modules' to facilitate the seismic assessment process. Each module undertakes a specific part of the assessment process, such as defining seismic demand, determining the in-plane capacity of a building, reporting, etc. These modules are facilitated by way of a web-based application that guides an assessor through a process.

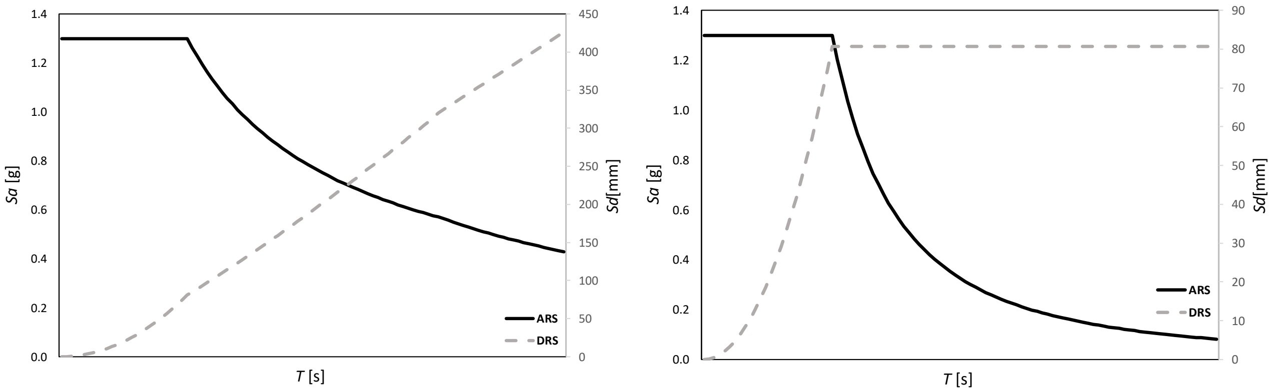
The system is material and construction agnostic to enable it to be applicable to as many types of buildings as possible. Unreinforced masonry (URM) construction is prevalent worldwide and is particularly vulnerable to earthquake loading. URM also requires specific analysis techniques to address the unique in-plane and out-of-plane failure mechanisms that can manifest, which are included in OSAS.

2.1 Demand

OSAS requires a seismic hazard to be defined for the region that is being assessed. For the system to be used to determine compliance, the hazard must be derived in a manner that is consistent with the underlying safety philosophies defined by the authority for that jurisdiction. Commonly, that would be an earthquake intensity corresponding to a 500-year return period event; however, it is possible to define other limit states.

Typically, the basis for determining the seismic hazard would be traditional probabilistic seismic hazard analysis, which may use historic earthquakes, known faults and propagation models as its basis. This type of model may be appropriate for tectonically derived seismicity; however, determining the hazard for induced seismicity is a complex and specialised area that can involve relatively short recurrence periods. These need to be extrapolated to make them compatible with compliance documentation, which can be associated with comparatively high uncertainty.

OSAS requires that the hazard is defined in terms of a universal hazard spectra (UHS). The OSAS uses displacement-based assessment techniques; therefore, the UHS needs to be defined directly in displacement terms, or use a UHS defined in acceleration terms that is able to be converted to displacement. Typically, the acceleration response spectra (ARS) defined in contemporary seismic standards are able to be converted to a displacement response spectra (DRS), as shown in Fig. 3 (a); however, there are ARS defined in certain international standards that are not able to be converted, as shown in Fig. 3 (b). Typically, these types of ARS are missing the ‘constant velocity’ portion of the spectra and when converted to displacement terms yield disproportionately large displacement demands for intermediate period building, which results in biased compliance outcomes for buildings with those dynamic characteristics.



(a) Compatible with displacement-based methods. (b) Incompatible with displacement-based methods.

Fig. 3 – Examples of UHS that are compatible and incompatible with displacement-based assessment.

Defining demand in this manner, as opposed to using more direct analysis methods, e.g. utilising a suite of earthquake records, is an important characteristic of OSAS because it allows capacity to be decoupled from demand. This allows OSAS to be able to interrogate a typology against many different demands to determine compliance for different geographic locations. This same trait allows exposure analyses to be undertaken for varying demand levels, which is discussed further in Section 4. Finally, decoupling capacity from demand provides the flexibility to rapidly respond to changes in hazard, which can be important in situations involving induced seismicity, where the understanding of the faulting mechanics can develop rapidly. This results in the hazard also changing more rapidly than tectonic seismicity.

2.2 Capacity

There are two main considerations when defining the capacity; in-plane and out-of-plane capacity. In-plane is the main capacity determination that is used for all building types; however, out-of-plane is particularly important for URM building as it typically governs the overall building performance. In-plane and out-of-plane analysis techniques are used to determine non-linear capacity envelopes. These are subsequently used to define the capacity of the building or element typologies.

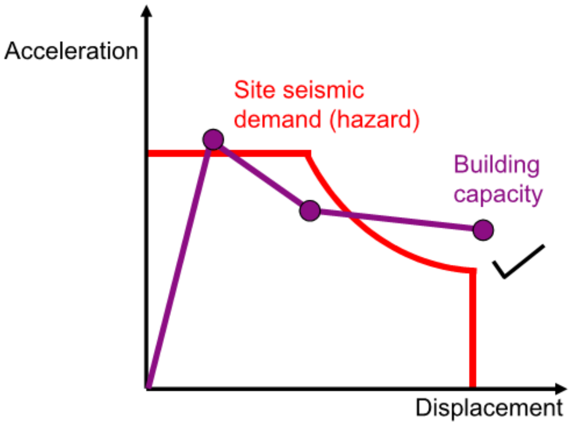
As with the demand, it is important also to ensure that capacity is consistent with the underlying safety philosophies for the region. This is expressed practically in most cases as the limit state that compliance is assessed at. In most regions with relatively modern seismic standards, compliance is assessed at the ultimate limit state (ULS); however, some regions use the collapse limit state (CLS) instead. The change from ULS to CLS also affects material property values. For the ULS, typically 95th percentile values are used in determining capacity; however, for CLS higher values are justified.

2.2.1 In-Plane

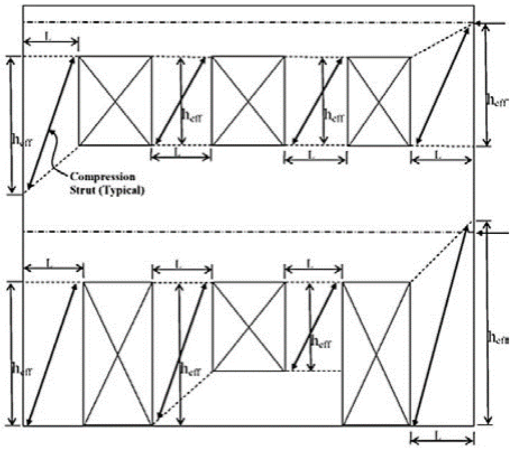
The assessment system requires a simplified analysis method in order to develop a non-linear capacity curve for the building. Once a number of these are undertaken, the curves can be grouped together to define the in-plane capacity of a building typology, as will be discussed in the following section. Non-linear static pushover (NLPO) is a commonly used analysis procedure used to inform the seismic assessment of existing buildings.

There has been extensive research and validation of NLPO as an analysis method to determine the likely non-linear response of buildings to earthquake loading. The theoretical basis for the NLPO approach is the equivalent linearisation approach for capacity spectrum assessment [3,7] and the substitute structure approach using direct displacement-based design (DDBD) [8].

The modelling approach used to find the NLPO curves for the assessment system is based on the Simple Lateral Mechanism Analysis (SLaMA) method. The SLaMA is a simple nonlinear analysis technique that provides an estimate of the global probable capacity of the primary structure as the summation of the probable capacities of the individual mechanisms [3]. The procedure simplifies a complex multi-degree-of-freedom (MDOF) system into an equivalent single-degree-of-freedom (SDOF) model, such that a SDOF equivalent non-linear pushover capacity curve can be compared to seismic demand in the form of acceleration-displacement response spectra (ADRS) in order to estimate the likely response, as shown in Fig. 4 (a).



(a) Capacity spectrum method; building capacity exceeds demand.



(b) URM rocking pier effective heights [3].

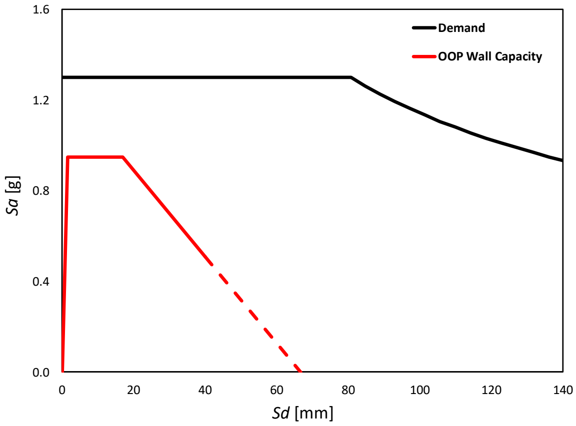
Fig. 4 – Non-linear pushover analysis.

When considering the in-plane strength capacity of URM walls, the individual mechanisms can be determined by identifying the piers and spandrels that make up the wall, and calculating the capacity of the different possible failure mechanisms of each individual element, as shown in Fig. 4 (b).

2.2.2 Out-of-Plane

Like the in-plane capacity, a simplified analysis method is required to develop a library of non-linear capacity curves for defining the out-of-plane capacity of each typology. The non-linear kinematic analysis (NLKA) is one method to undertake reliable calculations on the out-of-plane (OOP) structural performance of unreinforced masonry walls based on the geometry of the walls. The NLKA method takes into account both the elastic and non-linear behavior of the failure mechanisms. The NLKA method provides a balance between solution accuracy and method complexity; as such, it is a key part of both New Zealand [3] and Italian [9] seismic assessment guidelines and was chosen for the OSAS.

The inelastic displacement capacity of the wall is determined using virtual work methods and compared against the displacement demand, as shown in Figure 5 (b). Demand is determined using the spectral displacement, including modifications for wall position within the building and the wall properties.



(a) Example of out-of-plane wall failure from Christchurch earthquake [5].

(b) ADRS comparing OOP wall demand against capacity.

Figure 5 – Out-of-plane wall behavior.

2.2.3 Other Aspects

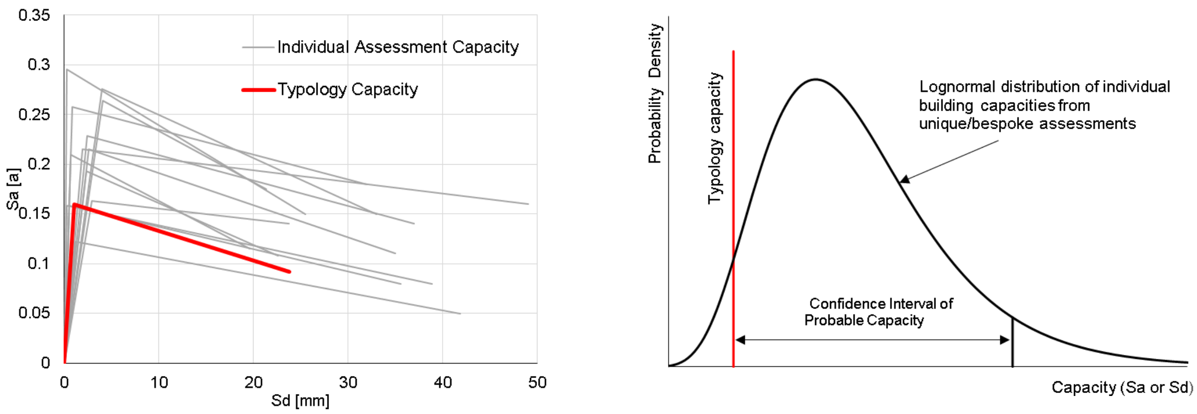
The NLPO and NLKA methods capture the primary building mechanisms; however, behavior can be influenced by several secondary mechanisms such as connection failure, building irregularity, foundation failure, etc. OSAS determines if a building is susceptible to failure related to any of these mechanisms and if it is the overall building capacity is limited.

2.2.4 Typologies

The OSAS relies on a library of pre-assessed non-linear capacity curves to allow assessors to make rapid seismic assessments of similar typologies and configurations of buildings. These non-linear capacity curves have been derived from unique seismic assessments made on a representative sample of the building population. Instead of having to undertake a traditional seismic assessment of every individual building, which can take a significant amount of time, it is possible to complete a seismic assessment in a matter of hours using the typology-based system that forms the basis of OSAS.

Typologies have been established using simple identifiable features that are linked to the seismic performance of the building or part of building. Records for many of these features, e.g. floor type, gable, material, exist already in databases maintained by the territorial authority. This approach makes it possible to undertake rapid seismic assessments utilising only fundamental building features, which if known can be semi-automated.

It is helpful to visualize how the assessment data is used to develop the typology capacity curves. Shown in Fig. 6 (a) are the non-linear capacity curves for one typology. The 'typology capacity curve' (shown in red) is established by a risk-based approach based on a statistical treatment of unique capacity curves that comply with the governing standards. The typology capacity is defined by the capacity estimate to achieve an acceptable confidence of the probable capacity, assuming a lognormal distribution of the individual building assessments, as shown in Fig. 6 (b). A typology capacity curve must contain a minimum number of unique assessments and have an appropriate coefficient of variation to ensure compliance with the standards.



(a) Individual push-over capacity curves and typology capacity curve.

(b) Typology capacity curve from individual assessments distributed lognormally.

Fig. 6: Establishment of typology capacity curves.

3. Application

3.1 Process

The OSAS is a means of undertaking accelerated building assessment and, if required, retrofit of many relatively similar buildings. It facilitates an end-to-end process to efficiently and consistently determine the compliance of a population of buildings. If a building is shown to be complaint, OSAS facilitates targeted inspection and automated reporting. If a building is assessed to be non-compliant, OSAS is used to undertake retrofit design to address the identified vulnerabilities. The process is shown in Fig. 7; the steps highlighted in dark blue comprise typology-based assessment and are the main point of difference to traditional assessment methodologies.

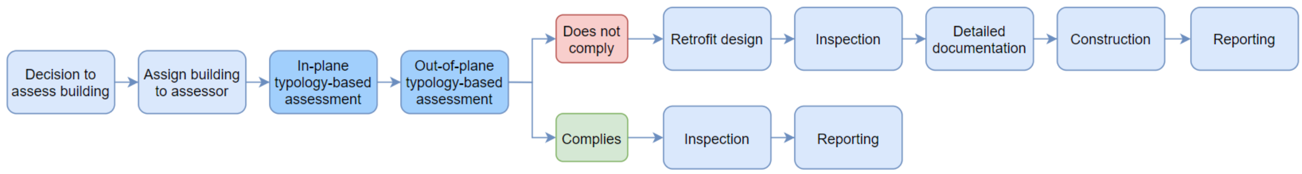
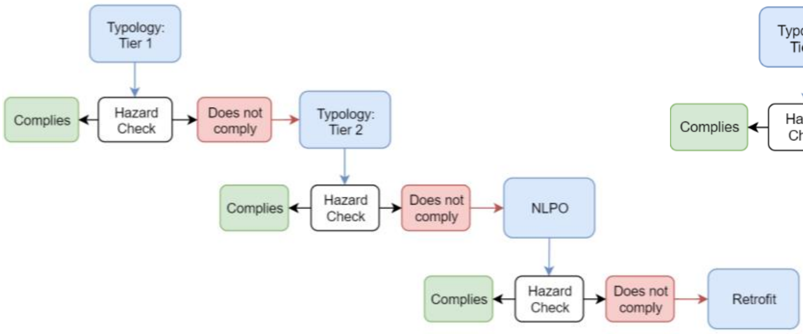


Fig. 7 - Building assessment process, each stage is a 'module' in the overall OSAS application. Stages in darker blue are expanded below.

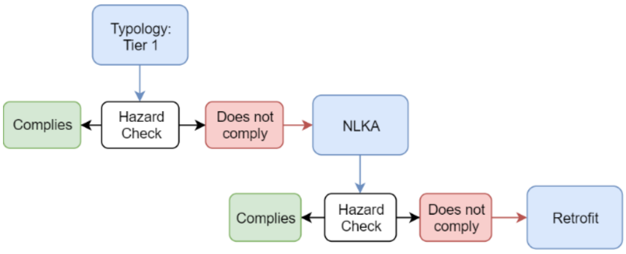
Within OSAS, a tiered approach is utilised when undertaking typology-based assessment of buildings. By using a tiered assessment approach, many low-vulnerability buildings can be shown to be compliant against the local demand quickly. Each successive assessment tier requires more building parameters, which better defines the typology. Each tier of the approach represents an assessment of increasing refinement. If a building is deemed to comply at one tier, then no further assessment is required and only a final inspection is required to confirm that the building conforms with the typology that it has been assessed under. If the building does not comply, then it passes to the next tier of the assessment system. This adds speed, efficiency and cost-effectiveness to the system since it is not necessary to undertake detailed inspection of all buildings prior to assessment.

The typology-based assessment process is shown in Fig. 8. At Tier 1, the defining characteristics of a building, or part of a building, are established from either databases or inspection and the corresponding capacity determined from the typology curves; compliance can then be determined by comparing building capacity against demand. For in-plane assessment, if a building is found to not comply following a Tier 1 assessment, it may still be shown to comply by using a more accurate Tier 2 assessment. If a building cannot be shown to be compliant at Tier 2 then a bespoke NLPO analysis is undertaken using the SLaMA process, which is built into OSAS. The out-of-plane typology-based assessment process is similar to in-plane; however, it does not have the intermediate Tier 2 stage before proceeding to a bespoke NLKA, which can also be undertaken in OSAS. An intermediate step is not required since out-of-plane typologies are able to be well defined from relatively fundamental characteristics. This approach increases the efficiency of OSAS, since assessment scrutiny is commensurate to building vulnerability.

OSAS is a learning system that becomes more intelligent with subsequent unique assessments. This occurs by the results of each building-specific assessment being fed back into the typology catalogue and, in doing so, the reliability and applicability of the system is improved. Over time, this process results in there being fewer unique assessments required.



(a) In-plane.



(b) Out-of-plane.

Fig. 8 – Typology-based seismic assessment process.

If the bespoke NLPO or NLKA assessments shows a building does not comply, then the retrofit module of OSAS is used to undertake rapid conceptual retrofit design. The retrofit module uses inputs from a catalogue of pre-engineered strengthening solutions for typical building details. The details are selected by the assessor based on several factors, such as building construction, cost, technical efficacy, homeowner preference, etc. Once the appropriate strengthening solutions are selected by the assessor, they are assigned to the deficient building within OSAS. The in-plane and out-of-plane modules are re-run to reassess overall compliance of the building with the retrofit undertaken. This system allows an assessor to trial many different interventions rapidly to arrive at an optimised design. Once the design is confirmed, OSAS is used to produce construction documentation, manage contractor procurement and produce reports.

An important benefit of the OSAS is that all activities are centrally managed, which allows for robust quality processes to incorporated into all stages. It also facilitates proactive and consistent stakeholder engagement, which is critical when dealing with a large population of affected building owners.

3.2 Software

The OSAS is facilitated by way of a web-based application, an example of the user interface is presented in Fig. 9. The user interface is designed to intuitively guide an assessor through the assessment process and provides helpful and informative links, popups and tooltips. A web-based solution has two main advantages: the software can be accessed anywhere by any device including tablets and feature improvements can be deployed in real-time, without the need for the user to reinstall the software to their device.

The software is organized into a series of 'modules', which facilitate a specific area of the assessment such as demand, in-plane capacity, etc. The modules are selected from the tabs at the top of the user interface. Users enter data into text input fields, drop-down selection boxes and graphical interfaces. In regions where there are well-curated building databases, many of these field are able to be automatically populated; however, the user is required to confirm the data before the assessment can progress. The software collates this data to a single JavaScript Object Notation (JSON) encoded message, which is sent to the structural calculation software (SCS) via an application programming interface (API). The SCS performs all engineering calculations and returns the capacity curve corresponding the assessment tier being undertaken. The capacity is presented to the user compared against the location-specific demand, which enable the user to determine the compliance of the building.

The SCS was programmed in Python, since this programming language was relatively simple for structural engineers to learn. It was important to have structural engineers developing the SCS, since they had a fundamental understanding of the mechanics. Other software components were written in C# on the Microsoft .NET Framework by software developers.

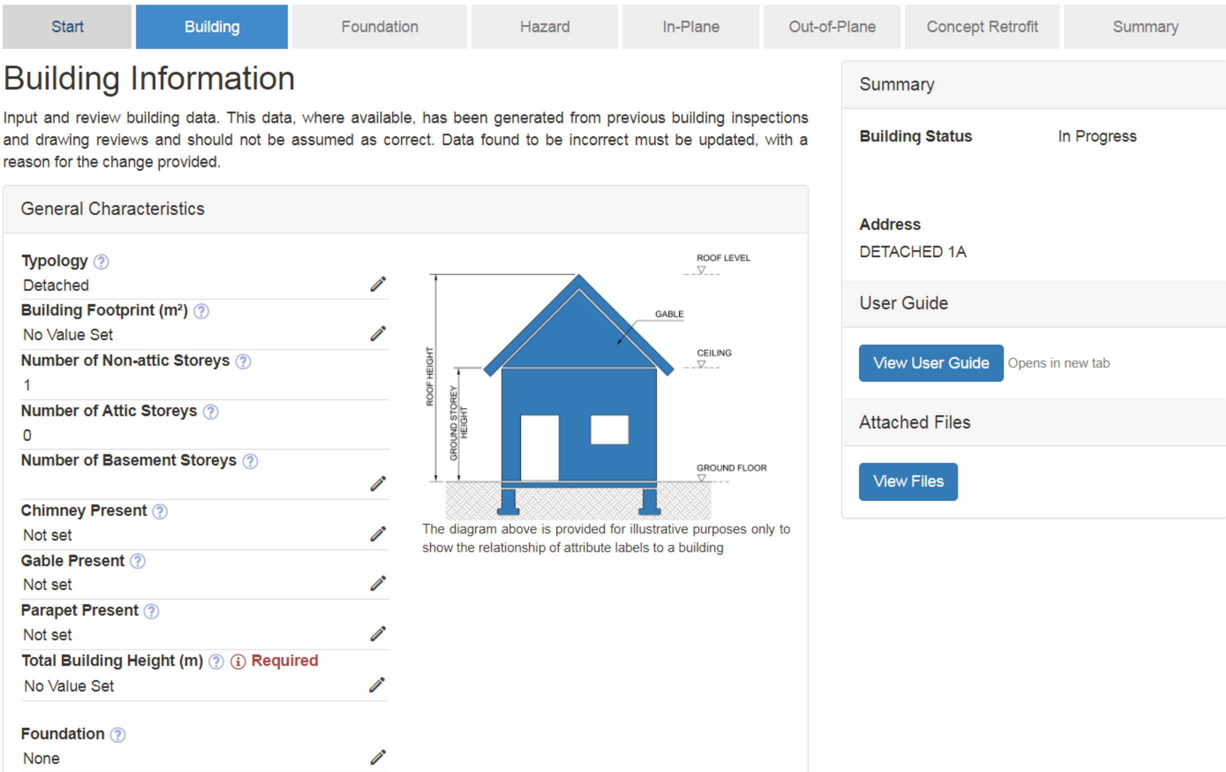


Fig. 9 – OSAS user interface.

4. Future development

OSAS is fully functional and being applied commercially; however, there are areas that continue to be developed to increase the functionality of the system. The process of creating new, and refining existing, typologies in on-going. This means that over time, there are less bespoke NLPO or NLKA assessment undertaken which increases the system efficiency. Furthermore, as the typologies become more refined the accuracy of bespoke assessments and typology-based assessments converge.

At present, OSAS includes capability to include local failure mechanisms that may affect the overall building capacity, such as connections, foundation, geotechnical, diaphragm, etc. This is facilitated by an extensive set of rules that describe acceptable bounds for various parameters. For example, a compliant diaphragm might require an aspect ratio of less than three when constructed from two-way spanning concrete. For buildings where these rules are not met, a bespoke assessment is required. Whilst the results of that assessment are subsequently used to update the rules, a more explicit assessment approach is desirable whereby element compliance is determined directly. Continuing the same example, this could be achieved by developing typology capacity curves for various diaphragm configurations that could be used to determine compliance directly against demand. This would increase the capability of OSAS to assess more unique buildings.

OSAS is deployed via a web-based application that facilitates on-site assessment via a mobile device. At present, the building features that define a typology are identified by the assessor from a prepopulated list. Since the assessor as already operating from a mobile device, the camera on that device could be used to leverage artificial intelligence, such as the IBM Watson platform, to automatically identify building features and define the typology. Developing this capability would not only increase the system efficiency, but also improve consistency by augmenting assessor decision-making.

The most significant area of future development is to combine OSAS with systems that facilitate hazard and propagation modelling. Propagation modelling is a means of determining the likely spatially distributed demands resulting from a rupture occurring along a given fault line, as shown in Fig. 10 for the South Island of New Zealand. This is useful in itself to undertake event-based impact assessments; however, it can also be repeated many times, for various faults and recurrence periods, to determine a probabilistic demand for all regions.

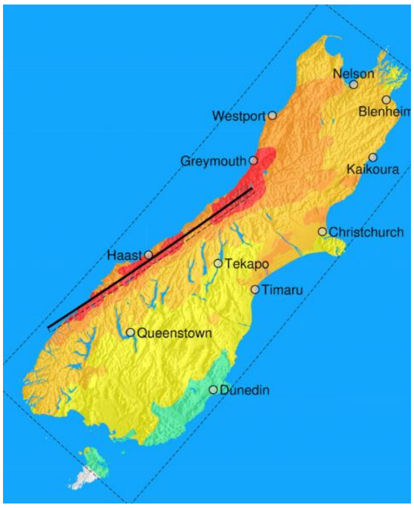


Fig. 10 – Earthquake propagation modelling [6].

Combining this type of hazard modelling with OSAS enables a powerful simulation tool that can be used to determine the impact of earthquakes with unparalleled resolution. For any earthquake source, or recurrence period, the resulting impact can be assessed directly; furthermore, the impact can be scrutinized at all levels equally, from individual buildings, to neighborhoods to entire counties. This type of platform has the potential to be used in all areas that are subject to seismicity to increase disaster preparedness and inform risk reduction strategies. However, in terms of global seismic risk, the greatest potential of the platform may be when used in lessor developed regions to devise pragmatic mitigation strategies that are implemented at policy level.

5. Summary

Traditional seismic assessment methods are well-suited to the appraisal of individual building vulnerability; however, they are inefficient when used to assess large numbers of buildings. Probabilistic seismic assessment methods can effectively determine the overall risk profile of large numbers of buildings; however, they are incapable of delivering building-specific outcomes. Where there is a need to undertake region or country-wide seismic assessment, due to induced earthquakes or changes in legislation, then a more efficient system is required.

This paper presented the background, technical basis and application of an optimised seismic assessment system (OSAS) that has been designed to be capable of assessing buildings on a country-wide scale, whilst delivering building-specific compliance outcomes. OSAS uses typology-based assessment techniques to deliver a step-change in assessment efficiency, whilst remaining compliant with the underlying safety philosophy of the region. The tiered approach to seismic assessment increases the system efficiency further, by matching the assessment scrutiny to the building vulnerability. OSAS is facilitated by way of a web-based application, which guides an assessor through a consistent process and enables mobile functionality. OSAS is currently being applied commercially and development of additional features and functionality is on-going.

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