


White Paper

Structural Commissioning

Technology to Validate Structural Performance and Quantify Risk

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Photo 1 - Building damage from the 2017 Mexico City Earthquake

1. INTRODUCTION

In every country around the world, current codes of practice for the design of buildings require that those structures are engineered to withstand the forces they are exposed to, especially from wind or seismic events. This helps to ensure that buildings have the needed capacity for the safety of their residents and the community. However, cities have not yet instituted a form of validation to ensure that the design intent was met in the inspection process. Recent versions of the design code provide performance metrics and techniques that offer the correct methods to use for this validation. An objective, one day test can be used to measure how buildings perform that would help ensure public safety.

It is troubling that the structural engineering community is resistant to such measurements, regardless of their primary ethical responsibility to safeguard the public. Embracing such performance measurements amounts to a check of their work, which might present a potential liability, if for any reason, the building fails to meet the requirements. Therefore, the performance of most buildings, both old and new, remains unknown to communities and residents. Yet, the building science research that was conducted to understand variations in building capacity clearly shows a portion of the existing building stock is weak. Also, construction defects in certain markets are very common. With infrastructure aging, more severe weather events and a global push towards community resilience, a proactive approach for risk mitigation regarding structural performance is necessary. Risk mitigation strategies are common on the federal level and within other global Disaster Risk Reduction efforts creating a positive environment for this approach.

As with other inspections, government, owners and insurers will need to take the lead to direct industry to be responsible and measure the performance of structures to ensure they were built correctly and that they continue to meet the needs of society regarding capacity. Structural Commissioning, as defined herein, is a simple ‘health check’ for a structure that measures the dynamic characteristics of buildings to provide objective feedback of the capacity of a structure.

Photo 2 - Engineers inspecting a building damaged from an earthquake

2. CURRENT STATE OF THE BUILDING INDUSTRY.

For over 100 years, City Governments have overseen the construction of buildings. Inspections take place to ensure structures are built as designed relating to its electrical, mechanical and structural components. As buildings have become larger and more complex, the supporting systems were often found to perform poorly, often resulting in lawsuits. As a result, and driven by government, the Building Commission industry took hold in the 1990's to provide a more rigorous inspection process to ensure the buildings systems were performing properly **(1)**. Yet, ironically, this commonsense approach did not include an aspect of structural performance. Although individual structural elements and components of a building are inspected during the construction phase, no 'performance verification' of the completed structure has been required. Historically, this was largely due to the high cost and complexity of such measurements. This lack of testing has left a void of feedback regarding the efficacy of the codes and the building process**.** Structural design codes have been making a slow progression towards 'performance-based design'. It is a more thoughtful approach to building design with the intent of having buildings withstand large events, while experiencing limited damage and remaining fit for their intended use. This concept is now becoming mainstream and is referenced in various codes around the world. The next step is to have the needed validation steps to ensure that these new and existing buildings meet their performance goals for their entire life.

Structural Commissioning is a verification step that is necessary to help ensure that the structures have the needed capacity to withstand the wind and seismic events they were designed to resist. It includes testing of the structure to measure its performance. This concept is consistent with the verification required through traditional inspections as well as the more advanced Building Commissioning process. With advancements in technology and recent updates in the codes where structural performance metrics and the best methods to perform the measurements are defined, this can be completed quickly and cost effectively. The industry should now embrace the objective measure of capacity through Structural Commissioning.

3. WHY THIS IS IMPORTANT

We know that the construction process and the materials used in construction have variability, which is why inspections are required and continue to evolve. Compounding the risk of poor construction quality, there is also a risk of limited oversight in the inspection process. Further, the building materials such as concrete and steel degrade over time. Additionally, over time, structures are impacted by storms, earthquakes and sometimes structural changes during their life. The end result is a population of structures, with varying or reduced capacity, that continues to degrade each year, yielding an elevated risk of damage or failure if a large force were to impact the structure. This risk may be apparent through the presence of visible damage or it may be totally hidden until large events occur. Visual inspection is currently the primary means of identifying damage in a building. This approach cannot identify structural weakness. If large events occur, then both the occupants of the building, as well as the entire community are impacted if the structure is found unusable or is destroyed. It may take several events to cause the ultimate failure of a building. And the incremental damage that occurs as a result of each event, as well as general wear and tear, is typically unknown and remains a hidden risk.

Since the 1970's in every country, building codes have been improved to increase the design requirements regarding the capacity for buildings. This was achieved in part through the knowledge gained from the testing of hundreds of structures for their capacity by the world's top researchers **(2)**. They developed a database of the dynamic performance of these buildings in response to wind and seismic events using advanced dynamic measurement techniques. These dynamic measurements were integral to improving the building design codes over the decades with the intent of achieving a robust building stock. Yet, the actual structural performance verification for the general population of structures was not required. This lack of feedback to the industry about each structure's performance has allowed for tremendous variability in the capacity of the overall population of existing structures. This was made clear in the research which showed the existence of many weak structures out of the hundreds that were measured. Some of the structures in the database showed a reduction in capacity that was the result of single earthquakes. All existing poorly performing buildings pose a heightened risk to the occupants of those buildings, as well as to the community. This lack of performance testing is a glaring weakness in the procedures for building and managing structures. But a mechanism to address this weakness exists through the performance metrics that have been published in recent building design code updates.

4. RESEARCH AND CODIFICATION

In 1989, NIST and NSF issued paper NISTIR 89/4153 titled *'Sensors and measurement techniques for assessing structural performance'* (3). It gave guidance and goals for structural performance measurements. Since that time, there has been a movement to develop and refine these methods. One primary recommendation in that report was the use of non-linear system identification techniques to measure the performance of structures. It was well known that the behavior of structures is 'non-linear' as they are exposed to larger forces. There is consensus on the appropriate non-linear analysis techniques to be used to measure the characteristics that define structural capacity. Now standards for building performance are referenced in the most recent updated ASCE 7-16 Design Standards (4). Taking dynamic measurements using the appropriate techniques to ensure buildings have the required capacity, consistent with the original recommendations, is available for new and old structures, at a reasonable cost. This Structural Commissioning capability will usher in an era of validating structural performance to help ensure public safety.

Only through testing can weak buildings be identified. The decades of research verified that there is a current risk to society that gets worse with age and large events. New Zealand has recently instituted a building performance requirement to help ensure buildings have the needed capacity to help reduce risk for their citizens. They are the first country to do so. They did this as a result of the tragic loss of life from the Christchurch earthquake (2011) where one weak building (CTV Building) collapsed, and 115 lives were lost. This building experienced three earthquakes in just a few months but was quickly put back into service immediately after each event since the damage was not clearly identified. Furthermore, on average, 50,000 people per year die from building collapses (5) and in 2017 there was $340 billion in insured property damage, around the globe due to severe events (6). The risk to the general population from weak structures may be far larger than believed based on the percentage of weak buildings identified in the early research.

With these structural performance metrics now in the design codes, and the ease with which technology allows for performance measurements of structures, it is incumbent upon the responsible parties to embrace Structural Commissioning. New and existing structures should be measured for their structural performance when they are built, sold and after damaging events. Without an objective method to identify high risk structures, the weak buildings will continue to pose a potentially fatal risk to owners, occupants and society. Government entities, owners, engineers and insurers have the responsibility to help mitigate this risk, which will continue to worsen, until wide adoption of a system to measure building performance is implemented. Once the method is commonly performed, the risk to our entire building stock could be understood in a short period, and high-risk structures can be identified.

5. SYSTEM THEORY

STRUCTURES ARE A 'SYSTEM' THAT NEEDS FEEDBACK

Each structure can be analyzed as a system. Currently, for the life cycle of a building, the system parameters that define how each performs are seldom measured. Therefore, there is limited feedback about the changes or degradation that occur to structures. Two of these system parameters are the frequencies of resonance and non-linear (structural) damping. These dynamic characteristics determine how a structure will respond to imposed forces as explained in the next section. The method of non-linear system identification measures the dynamic characteristics that provide the needed insight into structural capacity and can be used to assess the structure's risk profile.

System Theory dictates that any system is unconditionally unstable if feedback is not present. In practice, society does not know how our buildings are performing due to limited feedback. Thus, accurate and precise dynamic measurements provide the needed objective feedback to the 'system' to quantify the structure's performance. These measurements allow for a comparison of the measured response with that required by the society as epitomized by the design requirements of a code of practice. Acquisition of these measurements allows a comparison between the way that a structure behaves with the intentions of the code of practice, backed by design guides. This ensures that the design and building process met the requirements of the local culture, as interpreted by the experts who produce the documents that dictate the procedures for design. Also, by measuring the performance of existing structures a community obtains critical feedback information to ensure that their infrastructure continues to perform in a reasonable manner and has not degraded to a dangerous level over time. **This feedback is essential to quantify the risk profile for new and existing buildings. It is fundamental to community resilience.**

As shown below, system theory is applied to a structure:

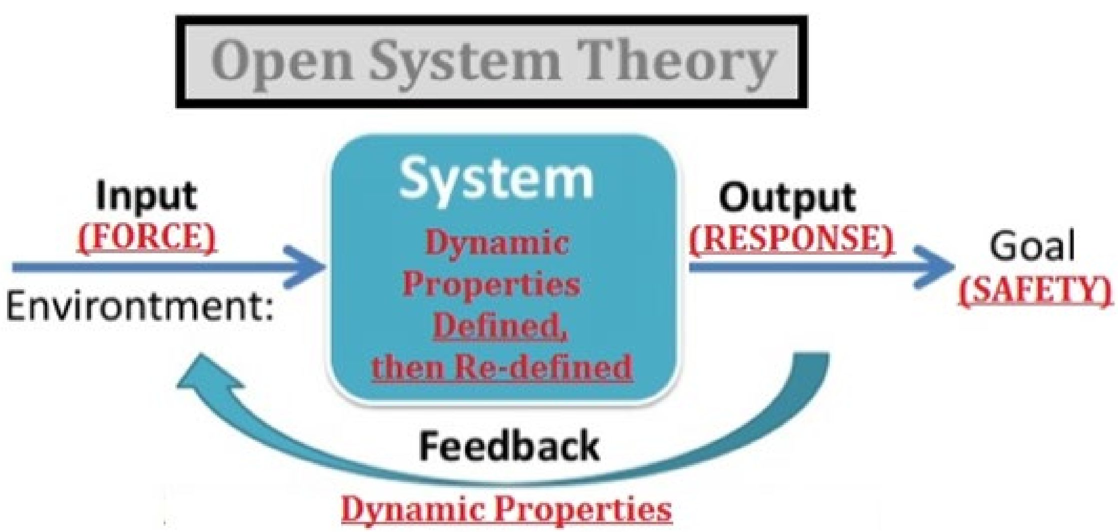

Figure 1 - Feedback loop for building system analysis

1) Input (Force) – Input forces are resolved to the principle axes of the structure. In nearly all design codes forces come mainly from one of two sources. In earthquake dominated regions the forces impinge on the structure through interaction with the ground motion. In wind-prone areas, the strength of the wind creates forces on the façade which, in turn, is transmitted to the structure.
2) System (Structure) – The system is designed to resist the imposed forces. The dynamic properties (specifically, frequencies of resonance and non-linear structural damping) are related to capacity. **They can be measured accurately to document capacity and how it changes over time**. These changes can be caused by damage from shock events such as earthquakes, wind and/or aging. These dynamic parameters are integral to understanding how a structure may respond to a force. As the parameters change, the response to a specified force will change as well. Therefore, the structure's risk profile changes every time there is additional damage. It should be noted that structural damping in the 'system' is a dynamic property of the structure. It is a 'modal' property meaning damping is different in each mode of vibration and is specific to a frequency of resonance. The fundamental mode of vibration has its own specific non-linear damping response. This is addressed further below.
3) Output (Response) - This is the measured **Response** of the structure to the **Forcing function**, as filtered through the **System**. The system, or structure, has certain dynamic properties relating to its ability to withstand that force, and for naturally occurring actions, the forces contain energy over a range of frequencies.
4) Feedback (Dynamic Properties) – This essential aspect is missing.

System shortcoming – With no method of feedback to validate the system properties of structures, there is a lack of reference regarding the capacity that any structures have when they are built. Seismic monitoring gives response information from large events but is not effective in managing changes to the 'System' because conventionally, measurements are made only during earthquakes**.** Additionally, using only the limited data from the relatively short duration of earthquakes, leads to a much less precise identification of system parameters than is achieved using the non-linear system identification methodology which works with data that occur continuously, at low amplitude. This provides the mechanism to track changes occurring anywhere in a structure especially after the occurrence of an 'event' (such as an earthquake or wind storm). Identification of these dynamic parameters provides an understanding of the risks associated with the structure and allows for a comparison with the design guidelines for stiffness and energy dissipation. Stiffness and non-linear structural damping change with damage which can be measured as 'system' changes.

6. STRUCTURAL DYNAMICS AND RISK

Structural Dynamics is fundamental to structural engineering and is integrated into the Finite Element modeling programs used for structural design and analysis. Codes of practice aim to present simplified procedures for the design process, and most designers can recite the code, but may not be as familiar with the science behind them. An element of structural dynamics is to view the response of a structure through a 'single degree of freedom system' model, and the overall structural response can be obtained by amalgamating several modes of vibration. For this 'system', the response equation below shows the relationship between displacement, frequency and damping (as well as the imposed force and the modal mass) for mode 'r'. Consider the following important points:

Response of as single degree of freedom (mode 'r').

$$X_r = \frac{F_r}{8 f_r^2 \zeta_r . M_r . \pi^2}$$

Where for mode 'r'

F is the force

M is the participating mass

f is the frequency of resonance

ζ is the damping ratio of mode r

Figure 1 - Formula for displacement for a 'single degree of freedom system

1) **Displacement, X, is directly proportional to $1/f^2$**, therefore, at a lower frequency, the same force induces a displacement that increases by a factor proportional to the square of the frequency difference. By knowing changes to the frequency, an understanding of how a structure will <u>displace</u> under a specific force is clear. Some design guides give norms associated with acceptable fundamental mode frequencies. (e.g. ASCE 7-16).
2) In the equation above, displacement, X, is inversely proportional to damping, zeta ζ. If damping is assumed to be a certain value in this equation (2% for wind and 5% for seismic is often widely used), but it is actually ½ that value, then the response, X, increases proportionally. It should be noted that Kareem's paper **(4)** supports the possibility that modal <u>structural</u> damping at high amplitude can be well below 5%. Also, research has shown that the structural damping at high amplitude can decrease below its high amplitude plateau value as a structure is damaged, and in turn would lead to an <u>increase</u> in response. Of course, this applies to a force that induces a response at a specific resonance and needs to be understood in that context. **Of importance is that this explanation is in contrast to the conventional thinking used in most codes**, because of the wide adoption of equivalent static behavior assumptions. Additionally, the response of the damaged structure may be much greater than previously understood because the building is more dynamically sensitive as evidenced by the dynamic parameters changing due to damage (even damage that is not immediately obvious). This is another reason and value of measuring the dynamic parameters with accurate methods.
3) The assumption that damping is proportional to velocity (viscous damping) is a mathematical convenience only and leads to several misapprehensions. It is not accurate and confuses engineers as to what damping really is. <u>Structural damping</u> (now referenced

in ASCE 7-16) changes with amplitude and as such, is smaller at low amplitudes. This behavior is incompatible with physical viscous damping behavior. Additionally, this shows that the velocity proportionality is not accurate, but while the assumption of friction damping gets the mechanism correct, the mathematical implications are incorrect. However, Wyatt's introduction of a friction function modified by a random process leads to an 'equivalent viscous damping' and provides an accurate and predictable damping model.

4) Displacement/drift is a primary performance criterion for buildings in seismic areas. **The displacement for a degraded structure will be larger if it has a reduced fundamental frequency, and a corresponding reduction in damping (at high amplitude) as dictated by the formula above.** <u>This poses a greater risk to the building since it will displace more due to the same design-required force</u>. If damping is small at low amplitudes of displacement, then the structure will move quickly to a larger amplitude, before damping increases. If damping were to take on a constant (5%) value (as suggested in codes), even at low amplitudes then the structure would take longer to reach a large amplitude. The difference in response under the two scenarios may not be trivial and under some transient excitation patterns could cause a 100% underestimate of the response amplitude of the structure. The non-linear nature of damping is important to consider and is currently ignored under all major earthquake and wind design guides and, in practice, by most engineers.
5) If a different model for damping (Wyatt model) is used, it has the benefit that it equates to 'an equivalent viscous damping' model, it allows the application of fracture mechanics to predict the form of the non-linearity of damping for any structure, and it allows the calculation of the expected excess response over current methodologies.

Therefore, measuring the dynamic parameters of a structure defines the 'System' parameters. This gives insight into how a structure will respond to a given force. It allows for a <u>proactive</u> understanding of whether the performance criteria established are likely to be exceeded under a specific event.

Risk to society - As buildings degrade, stiffness is lost and buildings become 'softer'. Under the same assumed loading force the buildings will displace more and experience damage more quickly and to a higher degree. Additionally, if the damping value is lower than expected, then the displacement will increase. With lower damping, high amplitude response will persist longer and more damage will be experienced. <u>Therefore, each incremental change in stiffness and damping will change the risk profile of a structure and will lead to greater displacements under future events.</u>

An elevated risk scenario – A simple example is shown below to illustrate that if the probability of experiencing a direct earthquake within 10 miles is assumed as X, then having an earthquake occur in a 40 mile radius is 16 times X, simply based on area, and of course ignoring the reality of fault lines and other factors.

Map - 1 - San Francisco Area

Earthquakes contain various harmonics of energy, meaning energy in different frequency ranges. As distance increases from the earthquake, high frequency energy is quickly damped out by the earth and the low frequency energy will travel further. The probability of having an impact from an earthquake further away is much greater than a direct hit. And in this scenario, the **low frequency energy can excite structural resonances and cause large displacements** when the excitation frequency includes energy at the frequency of a structural resonance. Three to ten story buildings can have natural frequencies that match low frequency ground waves of 1 to 2 hertz. If the conditions identified above regarding a degraded structure are present, which means that the response of a structure would be far greater than believed, then a disproportionate level of damage can occur from a relatively minor earthquake. Statistically for a specific location, smaller earthquakes further away are more likely to occur and the bulk of multi-family, schools, government and commercial buildings are the most vulnerable. When these events occur, they may cause more damage than expected, even under modest events. Also, the incremental damage from previous events is often patched and ignored, yet the capacity was decreased. There is a cumulative effect of this incremental damage. **The only way to understand this change in risk is to measure the system properties of each of the buildings.**

For example, in November of 2016, the Kaikoura earthquake hit the east coast of the South Island of New Zealand. The City of Wellington, 100 miles away, felt modest rolling ground motion. Yet, 80 buildings were damaged significantly and some beyond repair. Low frequency energy at 1-2 Hz caused damage to 6 to 12 story buildings. We measured the response of buildings in Wellington (see Wellington Case Study) after the earthquake and found that some of the buildings had low frequency values for their fundamental vibrational modes and structural damping values that indicated damage. This verified that some had low capacity. From our measurements we were able to identify those buildings that pose the greatest risk out of a group of 10 we measured.

Another example is the Central Mexico earthquake on September 19th, 2017 which caused a collapse of 40 buildings, killing 370 people, and injuring 6,000. **75 miles away** in Mexico City, 228 people were also killed from building collapses. This was on the anniversary of the devastating 1985 Mexico Earthquake which killed 10,000. Mexico City is built on ancient clay-filled lake beds with weak geotechnical conditions, which have their own frequencies of resonance which magnify low frequency energy. Additionally, the 'resonance on resonance' mechanism between the lake bed and the buildings was important to understand, and this condition exacerbated the dynamic impacts by amplifying the energy causing greater displacements and more damage. Although 40 buildings collapsed, hundreds were damaged and most were patched, thereby posing a continuing hidden risk into the future. **Measuring each building's dynamic parameters can help identify high risk structures to help mitigate risk prior to the next earthquake.**

7. SOLUTION.

Building Departments and other Government entities should begin requiring dynamic performance measurements on structures consistent with the methods identified in ASCE 7-16. This Structural Commissioning step quantifies a structure's performance as part of the building process. The dynamic performance measurements that have been performed for the last 40 years, once took months to accomplish, but it is now far less expensive, due to advancements in technology. A simple cure to this lack of information is to require dynamic measurements at the end of construction or a rehabilitation process through the building departments that approve the work. Checking these performance requirements is consistent with the inspection process and is a commonsense approach to ensuring structural performance as required by the codes.

The complex nature of the dynamic properties that are measured to define a building's performance can be simplified into a straightforward index. Below is a bell curve of a large portion of the global database of measured structures. Each dot represents a structure in the database. The 'Risk Ratio' is an index that reflects the ratio of the measured dynamic characteristics for a building of a certain size compared to the expected characteristics for that building if it meets its design intent. A '1' represents a building that has an appropriate level of stiffness to resist forces in most of the world. This index can be adjusted regionally, if the area has specific, more rigorous performance requirements. The buildings rated below 0.5 represent the population of structures that is well below the expected capacity needs. These buildings may be high risk and are likely to get damaged to modest wind and seismic events.

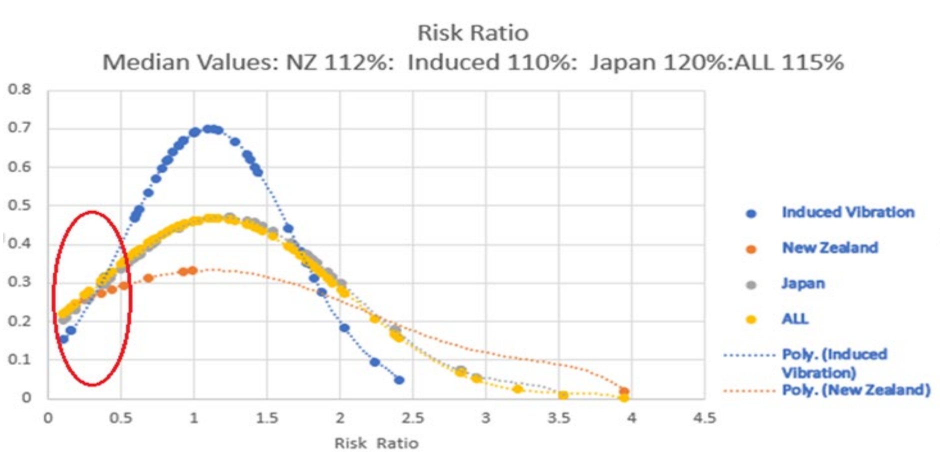

Figure 3 - Risk Ratio graph showing bell curve of structural capacity

Building performance standards continue to evolve. But the techniques for taking the dynamic performance measurements are now well defined. Society needs this objective feedback process to ensure buildings are built as intended and that existing buildings continue to have the capacity required. This information creates a mechanism for validating the construction methods to achieve their goal for those purchasing buildings who expect, and deserve, the capacity they are promised. With an aging infrastructure, urban areas need to be resistant and resilient to catastrophic events. Tracking performance on all structures will give verification that structural performance remains acceptable to the community for the long-term.

8. CONCLUSION

Structural Commissioning is a commonsense approach that uses objective measurements to validate building performance to help ensure public safety. If the industry continues to build structures without verifying capacity, they will perpetuate a climate where there is no understanding of the risk for certain structures. With the Codes now referencing the appropriate methods to do this analysis, it becomes incumbent for developers, owners and engineers to ensure the design intent was met. Ignoring any form of validation, even if it's not specifically directed by building departments, will prove to be a trailing liability for all parties. As we go towards performance based design, this Structural Commissioning step will be a requirement. It is the only valid method for such an assessment.

Key Takeaways

- A one-day measurement will establish the dynamic characteristic of a building to validate that it was built as intended and consistent with design requirements. This is an important level of feedback for engineers, owners and communities.
- As each building ages, or is impacted by storms or earthquakes, changes can be quantified. This will help expedite re-occupancy after events and if repair to damage is needed.
- Purchasers of buildings can understand if they are buying a structure which needs repair.
- Structural Commissioning will create a mechanism that will improve the building stock over time by allowing professionals and code committees to understand how buildings perform and if they present a risk in the context of the codes.

References

(*) The following abbreviations stand for these accreditations, degrees and honorary organizations:

AO – Officer of the Order of Australia
DSc(Eng) – Higher doctorate from University College London
PhD – Doctor of Philosophy from University College London
FRSN – Fellow of the Royal Society (New South Wales section)
FIStructE – Fellow of the Institution of Structural Engineers
FAIB – Fellow of the Australian Institute of Building

FIEAust – Fellow of the Australian Institute of Engineers (Structural Division)
FRMetS – Fellow of the Royal Meteorological Society

- The Order of Australia was awarded for services to Engineering. Australia no longer uses the old UK system, but in general terms the AO is equivalent to a British knighthood.
- A PhD is a formal qualification from a registered university, normally takes five years, and the work makes a contribution to a professional study area.
- A DSc is a higher doctorate, and the work must make a fundamental contribution to a field of study. A DSc normally takes a minimum of 20 years of research study.

The institutions of Structural Engineers, Australian Institute of Building and Engineers Australia are professional bodies responsible for organizing professions in the British Commonwealth. To obtain membership you must have a recognized degree in an appropriate subject, together with three years of professional experience in that field. The Fellow grade of membership is for senior professionals within the field. The Royal Society only accepts applications for fellowship from people who have a long record of serving at a senior level in one of the professional institutions. The Royal Meteorological Society is slightly different in that it is a learned society for applicants who are proposed by members, work professionally, and have a keen interest in meteorology (similar to the ASCE in civil engineering in the USA). The entire system operates in much the same way as licensing works in the USA

(1) The General Services Administration of the US government has established guidelines for Building Commissioning https://www.gsa.gov/cdnstatic/BCG_3_30_Final_R2-x221_0Z5RDZ-i34K-pR.pdf . Also there are industry associations such as the Building Commissioning Association https://www.bcxa.org/ which provide industry guidance for commissioning of buildings.

(2) Since 2004, the Vortex Winds (https://www.vortex-winds.org/) portal has offered tools for wind engineering design. On that site is a publicly available database with 330 buildings where the dynamic parameters (frequency and damping) for in-service structures were measured for their response to both wind and seismic forces. STRAAM uses this information, and processed the response data to show the 'bell curve' of structural performance on our literature. http://evovw.ce.nd.edu/damping/dampingdb_noauth1.php.

(3) NISTIR 89/4153 https://nehrpsearch.nist.gov/article/PB89-235865/XAB . This paper produced in 1989 identifies the needs and goals for structural performance assessments.

(4) ASCE 7-16 Design Standards - Paper Titled ' Tall Buildings and Damping: A Concept-Based Data-Driven Model' by Ahsan Kareem regarding 'structural damping' now referenced in ASCE 7-16, page 753 . https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29ST.1943-541X.0000890 .

(5) Statista.com is a website with the number of people who die each year to earthquakes. https://www.statista.com/statistics/263108/global-death-toll-due-to-earthquakes-since-2000/. The World Bank also provides information regarding these losses which can be found in the Disaster Risk Reduction Portal.

(6) The Insurance Journal publishes loss data for the insurance industry. https://www.insurancejournal.com/news/international/2018/04/24/487161.htm

Further reading

Global Research supporting the use of low-amplitude methods.

There are three major contributors to this field, however, there are thousands of researchers who are involved with wind and seismic engineering who have advanced these building sciences and have the skills to apply these methods. The original researchers are:

1) Dr. Alan Jeary (STRAAM Group, USA, formerly University of Western Sydney, City University of Hong Kong and Building Research Establishment, UK);
2) Dr. Ahsan Kareem (University of Notre Dame, USA), and;
3) Dr Yukio Tamura (Tokyo Polytechnic University, Japan).

Together they have published approximately 500 peer reviewed papers relating to structures. Their work and the contribution of hundreds of others have helped establish the fundamental methods for assessing structures using dynamic techniques in the field of wind engineering. There is international consensus on the utilization of these techniques.

Additional supporting and publicly available information.

Natural hazards Modeling Lab (Kareem).
https://ceees.nd.edu/research/nathaz-natural-hazards-modeling-laboratory

Global Center of Excellence for Wind Engineering (Tamura).
http://www.wind.arch.t-kougei.ac.jp/system/eng/contents/code/research_program.

Book referencing the Dynamic Signature of structures
https://books.google.com/books?id=DrlAjyUtbE0C&pg=PA443&lpg=PA443&dq=structural+dynamic+signature&source=bl&ots=25bf7HwFSV&sig=MLTbxdan6kX-Ol7wg2iEj5XXKcc&hl=en&sa=X&ved=0ahUKEwjstZmL4bLaAhWMFHwKHcV1C7M4ChDoAQgmMAA#v=onepage&q=structural%20dynamic%20signature&f=false
Topics on the Dynamics of Civil Structures, Volume 1, Proceedings of the 30th IMAC, A Conference and Exposition on Structural Dynamics, 2012

Amplitude dependency of damping
https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=13&cad=rja&uact=8&ved=2ahUKEwji-Zm30ZnkAhWFwVkKHdzUDukQFjAMegQIAxAC&url=https%3A%2F%2Fpdfs.semanticscholar.org%2F607d%2F25326844a1c33e7336b86b075cee797082b0.pdf&usg=AOvVaw0fe4osglObVFxuvGu4-slN
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Frequency and Damping measurement
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2004, World earthquake Conference.
https://www.researchgate.net/publication/284656408_Establishin_non-linear_damping_characteristics_of_structures_from_non-stationary_response_time-histories

Establishing non-linear damping characteristics of structures from non-stationary response time-histories. December 1991. Structural Engineer 70(4):61-66. Alan Jeary

RANDEC for structures
https://arc.aiaa.org/doi/abs/10.2514/3.57251

Damping and stick-slip implications – damage identification
https://books.google.com/books?id=56dwDwAAQBAJ&pg=PA61&lpg=PA61&dq=jeary+damping&source=bl&ots=JI6mDtDGON&sig=ACfU3U13wY0aUcc9Xas7qWHDig62Nm9h7g&hl=en&sa=X&ved=2ahUKEwji-Zm30ZnkAhWFwVkKHdzUDukQ6AEwEXoECAkQAQ

Random Decrement Technique for Modal Identification of Structures
https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=32&ved=2ahUKEwj65eH41JnkAhWG2FkKHeWADsE4HhAWMAF6BAgCEAI&url=https%3A%2F%2Forbilu.uni.lu%2Fbitstream%2F10993%2F12240%2F1%2FPAP022.pdf&usg=AOvVaw1zf9l7pu-HYt0T_1f4z80g

- December 2006 Conference: International Conference on Experimental Vibration Analysis for Civil Engineering Structures - EVACES 2007 At: Porto, Portugal

Largest Natural Hazard Organizations – Global movement on Risk Reduction

UNDRR - United Nations Disaster Risk Reduction https://www.unisdr.org/ (4200 cities have signed up for the 'Making Cities Resilient' platform. (https://www.unisdr.org/campaign/resilientcities/cities) ARISE is linked to this organization and provides resources for Cities in the MCR program.

GFDRR – Global Facility for Disaster Reduction and Recovery https://www.gfdrr.org/e. Driven by the World Bank, this organization is working to focus on disaster mitigation and recovery in the third world.

EMI – Earthquakes and Megacities - https://emi-megacities.org/about-urma/

Wellington Case Study – Provided on the following pages

Case Study - Wellington, New Zealand *(3 of 4)*

City Uses Performance Measurements from Ambient Vibration to Identify Structural Risk Profile for 10 buildings.

STRAAM Group, Inc.

How the measured Building Performance was used to quantify Risk.

Project History

On November 14, 2016, Wellington, the Capital City of New Zealand, was impacted by the Kaikoura Earthquake, the second largest in their recorded history which occurred 100 Km to the south. The quake was a 7.8 magnitude event and impacted Wellington significantly by damaging many structures and the port area. The City experiences earthquakes regularly and sits on 4 major faults in one of the most seismically active regions in the world.

City Council's Dilemma

The challenge for the City managers after an earthquake is to assess and repair damage so they can reoccupy buildings and try to get the City back to normal. In their efforts of assessing structures after Kaikoura, they hired high quality seismic engineers who followed proper **code required** methods to do the Structural Assessments on buildings. However, in some cases, the Assessment Reports for the same buildings prepared by different engineers had **greatly varying results** and recommendations. This created a serious concern for City managers since each Report has greatly varying required actions to be taken by the City. *It became clear to City Managers that a less subjective and more accurate Structural Assessment method is needed in their case to add clarity and certainty to the process.*

Figure 1- City of Wellington, New Zealand

STRAAM's Solution

The STRAAM Method uses the principles of structural dynamics and fracture mechanics to Measure the Performance, Determine the Stability and Understand the Risk of a structure. A week after the quake, STRAAM Group, and their licensed partner Mainmark were contracted to objectively measure the dynamic performance of ten City owned buildings and provide ten Structural **Dynamic Signature Assessment Reports**. The City was not aware that such a service existed prior to being approached by STRAAM but saw the potential **value that objective measurements** could provide.

Figure 2 - Some City owned buildings assessed by STRAAM

STRAAM and Mainmark mobilized in a week and measured the performance of all ten structures in five days. The Dynamic Signature Assessment measurements capture the dynamic response of the buildings which include the objective capacity related parameters of; frequencies of resonance, mode shapes and the non-linear damping response. Structures are always moving, in a well-designed building the occupants of the building will only feel the 'sway' of the building under extreme loading (very strong wind or earthquakes). The three parameters referenced above are simply the terms used to describe the rate of movement, and how much it displaces and distorts. However, they define the performance of the structure. STRAAM's proprietary technology has the required capabilities to measure the dynamic response from the normal excitation caused by light wind or traffic. These easily measured parameters are used to predict the response of the building at high amplitude which is then compared to code required limits.

STRAAM's Results

The resulting reports provided a structure specific risk profile based on the measurements and highlighted weaknesses in the buildings. Building codes around the world, and in New Zealand, require certain levels of stiffness, strength and ductility for structural design. The building codes and standards try to protect against 'severe structural weakness', soft stories, dynamic sensitivity and many other conditions which can lead to failure. **But currently, buildings are not measured for these critical aspects**. **STRAAM's methods gave objective clarity to these issues.** The STRAAM Reports explained the unique dynamic characteristics of each structure and provided a detailed report explaining the structure's performance in the context of the local building code.

After the risk profile was completed for all ten buildings, it was put into a 'bell curve' of structural risk. STRAAM has a database of 800 measured structures from around the world. Below is the bell curve of the risk profile created from each of the 800 building's measured response, where the Risk Ratio of 1 represents meeting the code's requirement. We circled buildings in the data based on a Risk Ratio of 0.5 or less, since that reflects a significantly reduced capacity and thus, an elevated risk level. The Dynamic Signature Assessment Reports and this comparison allowed City managers to see how each of the buildings performed relative to each other and to the other 800 buildings. **With this approach, the poorest performers are quickly identified.** This allowed the City managers to easily understand which buildings posed the greatest risk.

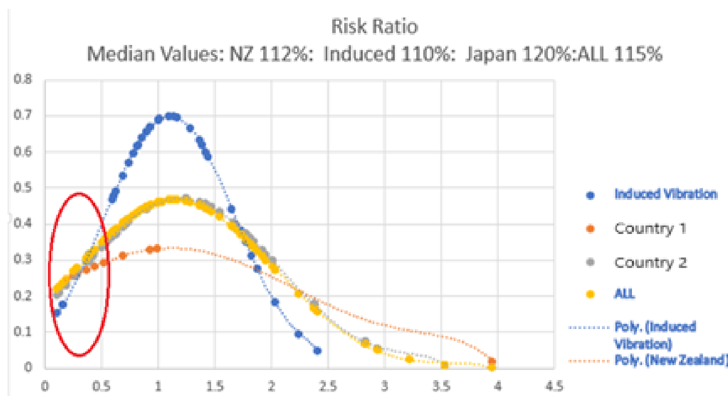

Figure 3 - Bell Curve of 800 measured buildings around the world

Added Value of STRAAM Method

For Wellington, and Cities around the world, these objective Dynamic Signature Assessment Reports and the Risk Ratio performance comparison to other structures, can help City managers to make informed decisions regarding specific structures based on their **objective and measured risk profile.** The value of understanding the risk associated with each structure is in the ability to determine where to allocate funds for repair, to assure that city buildings are safe for their intended purpose and by having confidence that each building is ready for occupancy after each event. The aggregated information in the bell curve gives clear performance information relative to their own population of structures to pick out weak 'outlier' buildings. <u>This database can be grown for each City to include assessments for all buildings in their inventory.</u> An additional and long-term value of this objective assessment is to help very accurately quantify damage from future events and aging. Once the 'Baseline' dynamic performance is established, then changes to this signature provide objective and actionable information relating to the new Risk Profile. Also, after a Baseline Dynamic Signature Assessment is completed, it is possible to install the technology for continuous monitoring with real-time performance information comparing to the Baseline, so **damage can be accurately quantified after events**. This can provide real-time feedback regarding building performance and degradation.

Improved Outcome and Resolution

Mr. Stephen Cody, The City of Wellington's *Principal Advisor on Resilient Buildings*, hired STRAAM Group and Mainmark. He said as STRAAM and Mainmark were hired, that '***every time we get an earthquake, even if it's minor, it takes a 'bite' out of the building's capacity. We need a way to better understand how the buildings are impacted each time it happens***'. He felt that objective measurements which relate to capacity could be a much-needed improvement to the **current Structural Assessment methods, which after Kaikoura, proved to be quite subjective** and left him in a difficult position regarding the recovery effort. He found the STRAAM Dynamic Signature Assessment Reports provided a critical data point regarding building performance and capacity. This helped him make important decisions regarding the recovery effort in Wellington.

An advancement for Community Resilience

As communities around the world look to improve their resilience to shock events, a fundamental aspect of this effort is to understand the overall capacity of the building stock. Using advanced technology like the **STRAAM Dynamic Signature Assessment gives accurate and detailed capacity related information** regarding each structure. This is essential feedback to city managers, owners and engineers to making wise decisions regarding building use, repairs and occupancy. It is in the best interests of the community and its residents.

(STRAAM's methods are supported by 40 years of research conducted around the world and leverages advanced technology to quantify structural performance in order to better manage the old and new infrastructure. It puts the measured response into the context of existing building codes and compares the response to a unique data base of hundreds of measured buildings as well as bridges and dams.

For More Information Please Contact:

Structural
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