In-situ Load Tests for lateral capacity

Why the Building Codes currently support performance measurements and *Building Officials* should require them.

1. Context

A recent building failure in Surfside, Florida has raised concerns about the degradation of our infrastructure from both extreme events, and by degradation from aging. An analysis of structural response that tracks degradation and damage so as to maintain a safe margin between the structure's actual integrity and its capacity limit is essential to help avoid tragedies like the Surfside occurrence. For the last 20 years the code of practice in the United States has been produced as a combined document addressing minimum forces expected for all types of loading. This code is the International Building Code (IBC), and it is modified and adjusted at intervals. The purpose of the code is to specify loads that are likely to occur, on average, just once in a certain duration. The risk of these loads occurring is standardized and this is also published as design standards or other documents which the IBC references. The job of designers and members of the design implementation team is to make sure that the completed project will withstand these specified minimum values of forces. The IBC mentions several methods by which a check on the ability of the structure to withstand the specified forces (and combinations of loads from different sources) can be assessed. The finished product is governed by engineering judgment, cost of different approaches, and various calculation methods for establishing the ability of the structure to withstand forces.

In this document, we are concerned with a structure's ability to resist lateral loads, as well as the cumulative effect of years of loading and degradation leading to a corresponding increase in the risk to society. In this respect the IBC(2018) contains the following statement: "The *loads specified herein along with the required load combinations have been established through research and service performance of buildings and structures".*

At present there is no requirement to assess the actual load carrying capacity of the structure. In this document we draw attention to the fact that the measurement of performance of structures is possible (through the measurement of the dynamic characteristics) and that the IBC specifically mentions the legal framework for this to happen, through the following paragraphs.

1604.6 In-situ load tests. The *building official* is authorized to require an engineering analysis or a load test, or both, of any construction whenever there is reason to question the safety of the construction for the intended occupancy. Engineering analysis and load tests shall be conducted in accordance with Section 1708.

1708 In-situ load tests
1708.1 General. Whenever there is a reasonable doubt as to the stability or load-bearing capacity of a completed building, structure or portion thereof for the expected loads, an engineering assessment shall be required. The engineering assessment shall involve either a structural analysis or an in-situ load test, or both. The structural analysis shall be based on actual material properties and other as-built conditions that affect stability or load-bearing capacity, and shall be conducted in accordance with the applicable design standard. The in-situ load tests shall be conducted in accordance with Section 1708.2. If the building, structure or portion thereof is found to have inadequate stability or load-bearing capacity for the expected loads, modifications to ensure structural adequacy or the removal of the inadequate construction shall be required.

The building official is allowed to specify in-situ load testing.

The measurement of the dynamic properties of a completed or existing structure is a method for achieving this.

2. Dynamic in situ load testing

The establishing of the performance under load using the measurement of dynamic performance can be used to establish the displacement per unit force characteristic of the entire structure. To be able to do this it is necessary only to measure the performance of the structure's principle frequency of resonance and the damping value associated with that mode of vibration. Both parameters are non-linear and careful analysis of them must be made. Of these, the damping parameter is of greater importance. Armed with these parameters a comparison with the values expected using IBC can be made, and a comparison of the actual performance with that expected can be made. In SEI/ASCE 11-99 the ways in which an in-situ load test can be performed are enumerated. The techniques referred to in this paper comply with the methodology of the standard.

Damping

Damping is a measure of the energy dissipation when a structure is vibrating in a resonance. On its introduction damping was named 'equivalent viscous damping'. (Viscous damping is the type typical of shock absorbers on a vehicle). The problem is that while this is convenient mathematically, buildings do not have obvious viscous dampers in them. In the 1970's a friction mechanism was introduced (Wyatt, 1977) which subsequently allowed the prediction of expected damping values.

Damping is affected by the amplitude of response and when the amplitude becomes larger, then there are other mechanisms of energy dissipation that affect response. This factor has prevented the earthquake and wind engineering groups from being able to compare values. However, with the measurement of the response at low amplitude, then the damping value associated with the structure only and excluding the soil-structure interaction is obtained.

If the low amplitude response is analyzed, then the frequency and damping values apply to the structure only. At large amplitudes the energy dissipation comes from at least two different sources. However, a large value of damping shows increased energy dissipation (such as that caused by damage in the structure), and by using only small amplitudes of response the second mechanism (energy dissipation in the soil) is eliminated and the remaining information gives information about the structure

If the measurement instrumentation is sensitive enough, then the forces required are small and can be caused by a breath of wind, by nearby traffic, the movement of people or similar mechanisms.

The following diagram shows the difference between mechanisms for low amplitude and high amplitude responses:

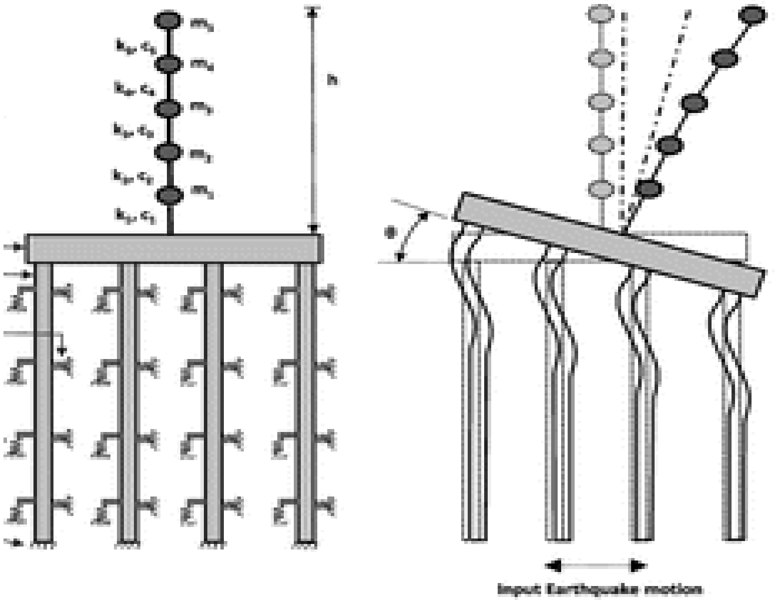


Figure 1: A structure depicted with masses and stiffness elements undergoing small response amplitudes (on the left) and large amplitude response (on the right showing movement in the foundation).

The damping for a building has been researched to a sufficient level that predictors are available for non-linear damping values, and these are quoted by the commentary to the Japanese code published by the Architectural Institute of Japan (AIJ). There is also considerable information available about damping in bridges.

The damping characteristic for a building is shown in Fig 2.

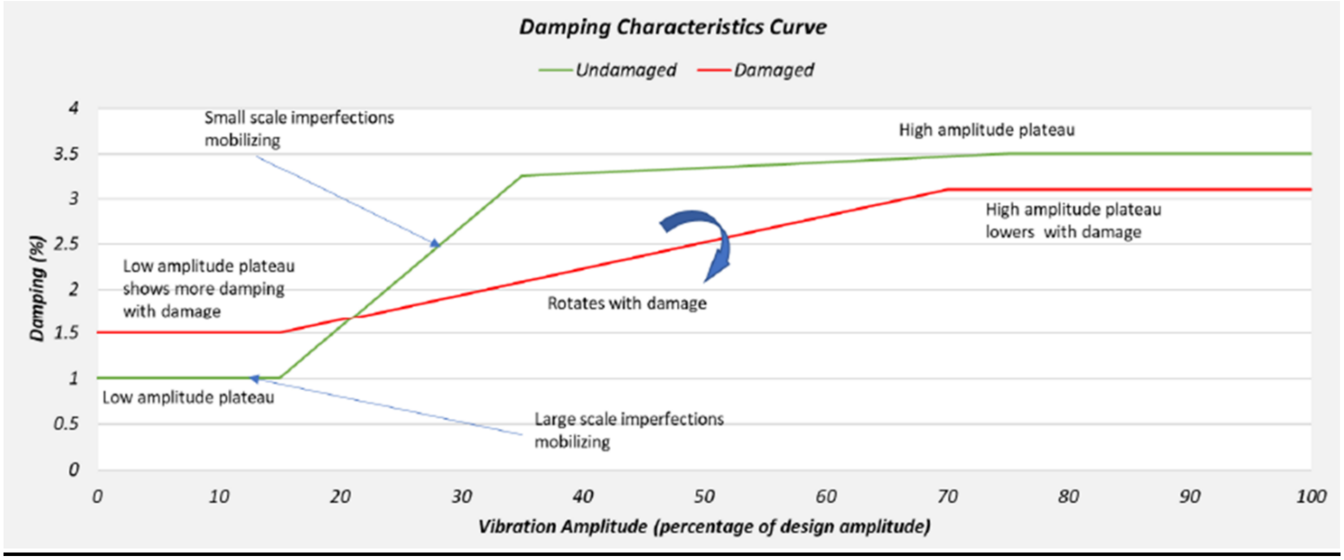


Fig 2: Generalized damping characteristic for a building.

In figure 2 the green line represents a three-part curve showing the damping characteristic expected for a new building. The low amplitude part of the curve is governed by attachments to other structures and the interface of large elements. The center part of the curve is a function of imperfections within the materials of construction (for instance cracks and smaller imperfections). The imperfections are mobilized at larger amplitudes, making imperfections elongate (as predicted by the science of fracture mechanics). When there are no more imperfections that can be mobilized, all energy dissipation mechanisms are used up and the damping characteristic reaches the third part of the curve.

The damping characteristic for bridges is similar, but the proportion of influences from geometric form, materials, and aerodynamic damping are modifiers.

If the structure is damaged, then the damping curve has a characteristic represented by the red curve in figure 2. At low amplitude cracks appear between large elements, in the center portion of the curve the characteristic rotates, reflecting the elongation of imperfections and an increased number of larger imperfections and cracks. The third part of the curve lowers, reflecting a smaller number of small imperfections.

Damping measurements are notoriously difficult, but modern developments and the use of new algorithms (characterized in a paper by Dr. Ahsan Kareem) make the estimation of damping to better than 5% of the measured value a straightforward process.

Measurements of the dynamic performance, if made within the so-called linear elastic zone (governed by a constant displacement per unit force characteristic) and justifying the use of Young’s modulus of elasticity, allows the extrapolation of the measurements to any point within the force displacement characteristic up to the limit of the elastic zone. The extraction of the force/displacement ratio is based on the use of Newton's second law of motion and is presented in the next section.

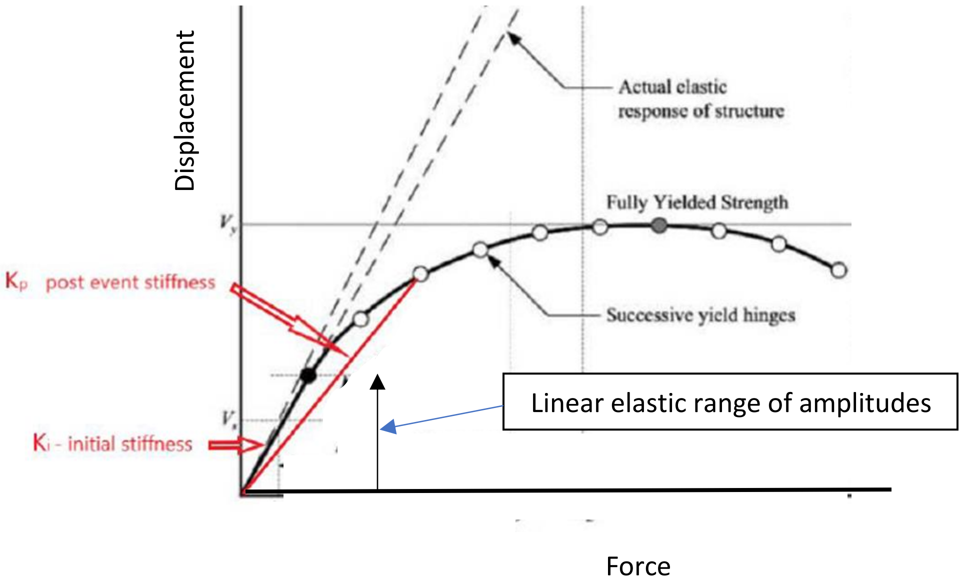


Fig 3: Force /displacement characteristic for an entire building

The black line shows the characteristics for both wind and earthquake considerations. The red line shows the effect of the presence of damage on the stiffness characteristic. The measured period (1/ frequency) of a structure is proportional to its stiffness in the elastic range.

The calculation of the slope characteristic from measurements of dynamic response is considered in the next section.

3. Estimation of capacity and comparison with code requirements

When Newton's second law of motion is applied to a single response at resonance, then the following equation ensues.

$$\frac{X_r}{F_r} = \frac{1}{8 f_r^2 \zeta_r M_r \pi^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where for mode 'r'

X is the displacement

F is the imposed force

f is the frequency of resonance

ζ is the damping

M is the mass

All parameters are modal quantities and when applied to the fundamental mode of vibration are closely correlated with the quasi-static method currently used for design.

If the ratio is calculated for any location inside the elastic range (consistent with being outside the low amplitude of the three part damping curve), and then compared with the response expected using the IBC specified forces, it is not necessary to know the mass of the structure, and measurements of only the frequency and the damping are necessary to compare the measured stiffness ratio with the expected, using the IBC.

Since codes change over time this comparison can be made for the conditions under which the original design was made and the current requirements.

When this comparison is made for measurements in the real world the following is obtained:

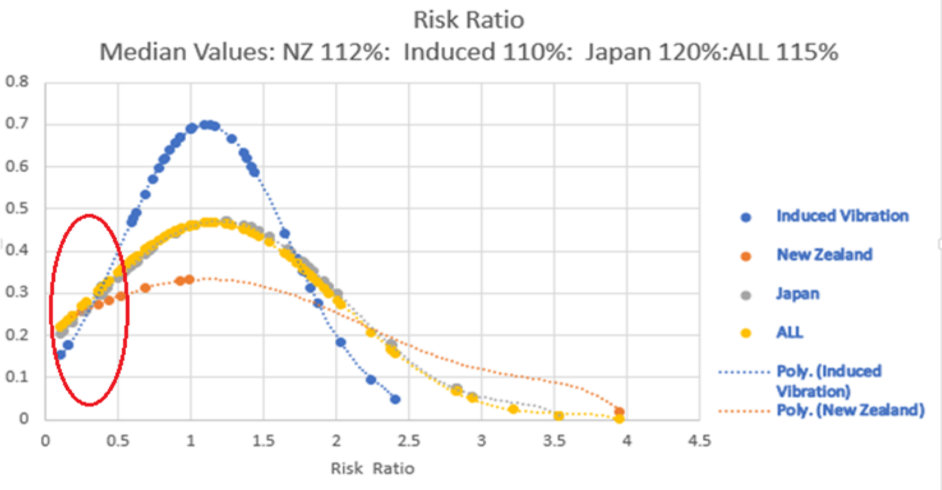


Fig 4: The risk ratio for full scale buildings from in-situ lateral, low amplitude load tests

The figure shows the results of tests in various parts of the world for buildings that are designed for a building criteria where both wind and earthquakes are the dominant forcing function.

The value of risk ratio = 1 in fig 4 shows that the performance of the building is just that required by the code of practice at the time of the measurements (and it is possible to compare with earlier versions of the code or with different codes used in other locations). The fact that a significant number of buildings had a risk ratio less than 0.5 shows that a significant number of structures are in a perilous or dangerous state.

The techniques are usable for all types of structure, although the detail is different. Additionally, the techniques are usable for the vertical response of structures, including for the identification of cavitation, washout and other effects on the vertical load carrying capacity of the structure. Unfortunate recent collapse events of both buildings and bridges are therefore discoverable using the techniques listed here, before there is the development of a failure mode.

4. Traditional visual inspection methods are variable

One of the buildings in Fig 4 was assessed by visual inspection. Two different post earthquake damage assessments were made using identical criteria in a visual assessment. The two assessments produced estimates of 80% and 30% respectively of the required capacity. Subsequently, the building was assessed by measurement of the dynamic response by STRAAM Group and confirmed the value of 30%. Additionally, a baseline measurement also includes mode shape measurements (the distorted shape the building takes as in vibrates at resonance). This has the added advantage that the area in which a stiffness anomaly exists is identified. If a baseline measurement is taken regularly the presence of sub standard and dangerous structures in our environment can be reduced and ultimately eliminated.

5. Conclusion

The legal path for a building official to require an in-situ test using the dynamic response of a building exists in the current US code of practice (IBC,2018). Its use could radically reduce the danger to the public posed by buildings that are in a dangerous state. The procedures are straightforward, and the data can normally be collected in less than one day. There is no reason to delay specifying such tests. The accumulation of this information in a baseline study when a building is completed will validate that the design intent was met and quantify accurately the capacity of the structure. Repeating every year would allow a complete understanding of a building's current state, and changes as time passes. If a structure experiences damage from wind or seismic events, or just from aging, changes in the capacity can be verified.

6. Example

The measurements of frequency and damping for the first mode of the structure (in this case a building) are measured and the amplitude of response is ascertained. The rate of change of both these parameters is derived from an analysis using the amplitude related random decrement function (Jeary, 1986). The expected frequency and damping at that amplitude are then calculated using the techniques listed in that paper.

The measurements were obtained from one force balance servo-accelerometer placed on the roof of this 54 meter tall building. The recorded data were analyzed in the STRAAM analysis center to yield the nonlinear damping and frequency characteristics.

The expected frequency is related to the height of the building. The expected damping is composed of a base value (a function of the frequency of resonance), and a rate of increase against amplitude conditioned by the material of construction and the amount of material participating in the vibration.

For this particular case the Amplitude Related Random Decrement is shown below.

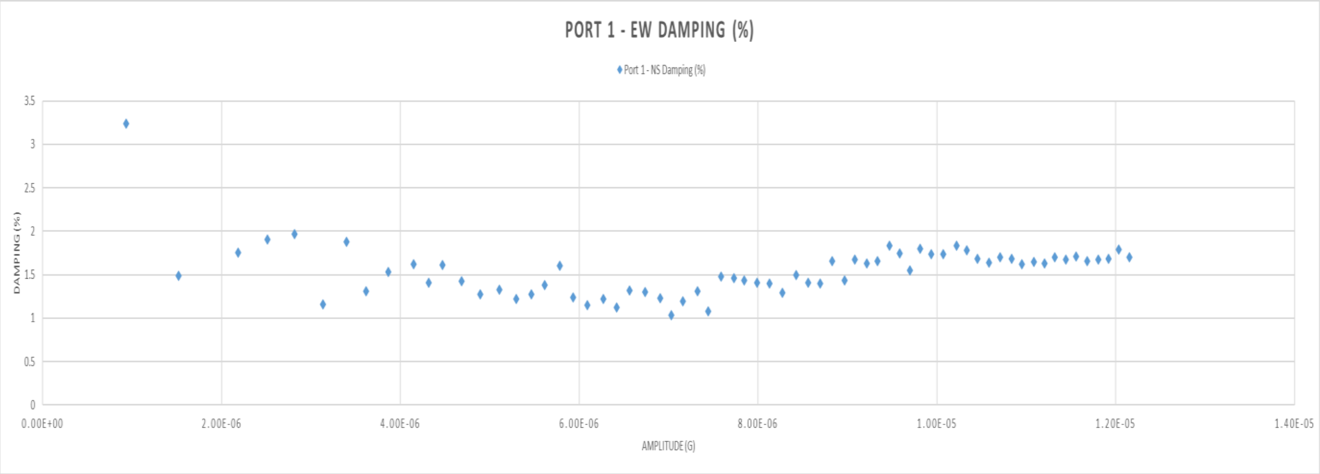


Fig 2a. Non-linear damping characteristic obtained from the Amplitude Related Random Decrement.

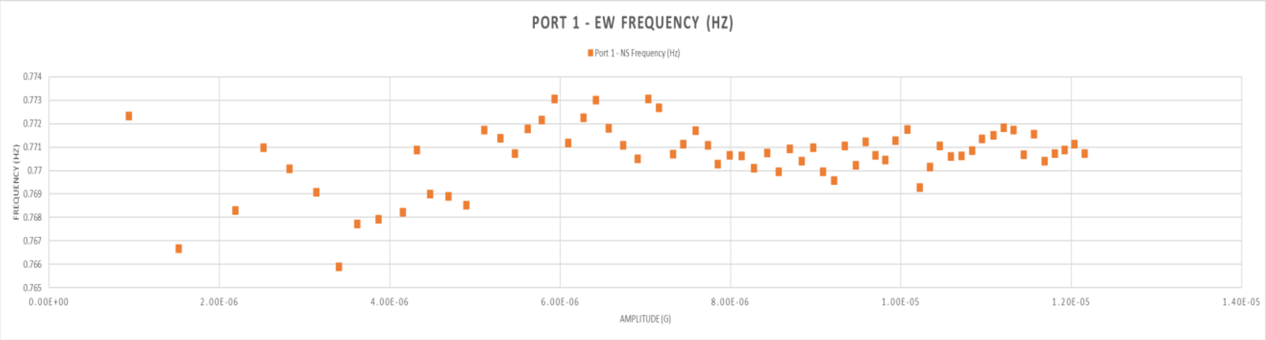
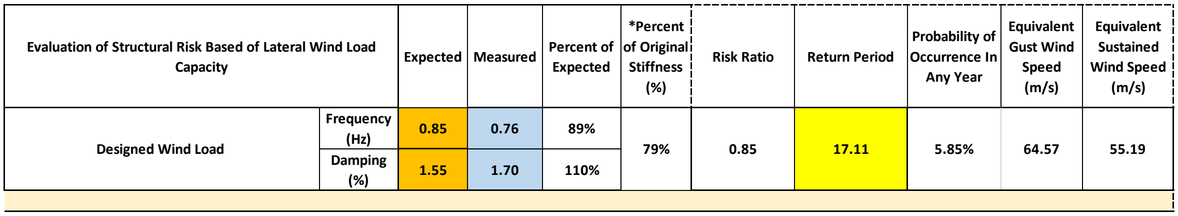


Fig 2b. Non-linear frequency characteristic obtained from the Amplitude Related Random Decrement.

As can be seen from Figs 2a and 2b, there is a slow increase in the damping characteristic and the frequency stabilizes to a constant value at amplitudes greater than 8 x 10^{-6}g.

Having obtained the four values for these two parameters, it is only necessary to evaluate equation 1 for the measured and the predicted values of frequency and damping at an amplitude of response within the linear elastic range.



Evaluation of Structural Risk Based of Lateral Wind Load Capacity		Expected	Measured	Percent of Expected	*Percent of Original Stiffness (%)	Risk Ratio	Return Period	Probability of Occurrence In Any Year	Equivalent Gust Wind Speed (m/s)	Equivalent Sustained Wind Speed (m/s)
Designed Wind Load	**Frequency (Hz)**	**0.85**	**0.76**	**89%**	**79%**	**0.85**	**17.11**	**5.85%**	**64.57**	**55.19**
	Damping (%)	**1.55**	**1.70**	**110%**						

* Field measurements do not separate the participating stiffness constributed from non-structurral element.

Note - Typcical design uses a 50 year return period meaning in any given year there is a 2% chance of occurrence for a storm of that magnitude to occur.

Fig 3: Analysis of the risk ratio from the measured data.

Wyatt T.A. -Mechanisms of damping. Symposium on dynamic behaviour of bridges. TRRL Crowthorne, UK . May 1977.

Jeary A.P. Damping in Tall Buildings – A mechanism and a predictor. Earthquake Engineering and Structural Dynamics. Vol 14, pp 733-750, (1986).