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The Risk Ratio – how it enhances integrity assessments

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ABSTRACT:

The Demand/ Capacity ratio is well understood by structural engineers as a design consideration for buildings and bridges. The 'demand' comes in the form of forces either from naturally occurring wind and seismic events, or from loading such as traffic in the case of bridges. Additionally, all structures, whether they were built as designed, or with flaws during construction that cause them to have a diminished capacity compared with the design intent, will degrade over time reducing the capacity side of the ratio. This is a risk to society that the engineers and owners have failed to quantify effectively. The risk to society increases over time and should be addressed in the context of the risk that is acceptable to that society consistent with codified forces extracted from locally measured naturally occurring events. We address the rationale for the use of a risk ratio, detailing the relationship between the actual performance of a structure and that required by codification. It is shown how the risk ratio provides a holistic measure of the integrity of a structure through the precise measurement of both frequency and damping for the fundamental mode of a structure (for buildings this is the first sway mode). Both of these parameters are non-linear, and care must be taken to establish stable estimates of the non-linear characteristics. Given this measurement it becomes possible to establish a risk ratio of the actual behavior compared with that expected from the requirements of the local code of practice. Both damping and mode shape anomalies can be used in conjunction with the holistic risk ratio to identify areas of severe structural weakness. The most important factor in this analysis is that the damping ratio is derived from a stick/slip model (based on fracture mechanics) which allows the establishment of an equivalent viscous damping value for all appropriate amplitudes of response for the structure. In turn this means that the change in a risk ratio before and after a severe even indicates the severity of any damage and allows a measured assessment of whether the structure's continued use is viable or not. This approach potentially supplies useful information for structures undergoing either wind or earthquake induced excitation. It also applies to bridges, where increase traffic loading, and the slow reduction of capacity must be quantified as the structure ages. The basis of the technique is contained in a 'gold standard' of induced vibration tests on 40 full-scale structures. The risk ratio also provides an index that can be used as the percentage risk per year of continued use of the structure.

KEY WORDS: SHMII-11; wind, earthquake, risk ratio, yearly risk of operation

1 INTRODUCTION

The continuing integrity of structures has been of considerable interest, especially with the increasing number of collapses and partial collapses in areas where such occurrences are unexpected. The process of establishing reasonable integrity has been slowed by awkward processes that rely heavily on visual observation. In this paper the authors present a methodology based on the measurement of the performance of buildings and other structures, so that a precise measurement of the ratio between the current state of a structure and that expected by code is calculated. This methodology is so powerful (and has been used on more than 100 structures that is has been used to identify severe damage even when broken structural members are hidden behind facades. The risk ratio can be used to indicate the continued risk of continuing to use a structure, and so it offers more than just an integrity index, but also a means of identifying when maintenance must be performed and when the end state of a risk that is unacceptable to a community indicates the end of a useful life. Additionally, if tracked over time the changing risk ratio can be used to indicate remaining life of a structure.

2 LOW AMPLITUDE RESPONSE IMPLICATIONS

With the use of very precise accelerometers, measurements of the response of a structure can be made at very small amplitudes. Spectral measurements show the noise floor occurring at 1e-10 g^2/Hz. which, at 1 Hz., represents the wavelength of visible light. It is uncommon to be interested in measurements at such small amplitudes in civil and structural engineering, and yet all practitioners use Young's Modulus for various reasons. Young's modulus is a ratio of Force and displacement and is approximately constant over a large range of amplitudes from very small until the limit of elasticity is reached. The implications of the linearity of the displacement/force ratio are extensive. The elastic range of response is applicable to both wind and earthquake engineering. It is only at very large amplitudes of response that the characteristic becomes non-linear, and this is when such effects as soil/structure interaction and ductility become important. Before the end of the elastic range the force/displacement ratio is constant (despite nonlinearities in frequency and damping) and is a representation of the structure's characteristic resistance on a holistic basis if the integrated force and the displacement of a point on the structure is measured. This information is useful to both wind and earthquake engineers.

3 INDUCED VIBRATION – THE GOLD STANDARD

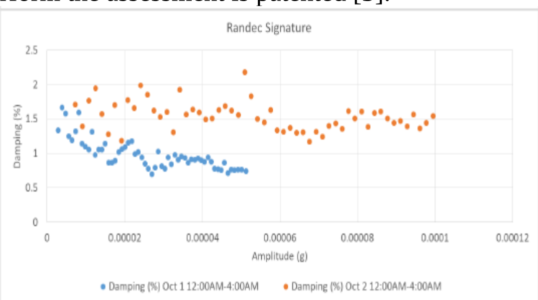
During the 1970's and 1980's the Building Research Establishment (BRE), in the United Kingdom, conducted a series of induced vibration tests of full-scale structures, using a four-unit vibrator system that produced a sinusoidal force of one tonne at one cycle per second and could control the frequency of excitation to a precision of 0.001 Hz. The vibrator system was used on forty structures [1] and included tests on buildings and dams. The quantity of full-scale tests is greater than the number of tests conducted by all other organizations put together. The measurement of the variation of damping in the BRE induced vibration testing enabled a predictor of expected damping values to be made.

4 MEASUREMENT OF NON-LINEAR DAMPING AND FREQUENCY

The two parameters that are of most benefit in establishing integrity of a structure are the frequencies of resonance and the damping ratio associated with a resonance. The fundamental mode of both buildings and of bridges is of the most significance. Both parameters vary with amplitude and the precision of induced vibration tests allowed their precise measurement across a significant number of structures.

4.1 The amplitude related random decrement

With the characteristics of non-linear damping established using precise measurements under induced loading, the random decrement signature [2] (introduced by NASA to identify fatigue damage on the wing of the space shuttle) was modified to produce a measurement of damping at a series of different amplitudes, using response measurements from random excitation only. This allowed the rapid assessment of non-linear damping. The refinement of the algorithm to produce the Amplitude Related Random Decrement signature, avoids problems with a singularity that can occur and reveals precise damping (and frequency) measurements over a range of amplitudes. The algorithm and associated equipment to perform the assessment is patented [3].



5 THE RISK RATIO

If the equations of motion for a single degree of freedom system are solved, then the following is obtained:

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

Where for mode 'r'

M is the participating mass
f is the frequency of resonance
F is the force
ζ is the damping ratio of mode r

Of particular use in the current context, is reformulating this equation to represent the ratio of displacement per unit force:

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

To use this relationship on full scale structures in the field it is necessary only to make measurements of modal mass, damping and frequency. If the fundamental sway frequency of a tall building is used, then the information becomes directly comparable with the design case. There are then two considerations:

1. A comparison of the measurement with the values expected when adopting a code of practice's philosophy.
2. A comparison of the measured parameters with those measured shortly after a structure is put into service.

In both cases these calculated ratios involve the elimination of the modal mass, and measurements or estimates of damping and frequency are the only requirements.

The calculation can the be expressed as a ratio of the measured performance to that of the expected, or the early-life displacement per unit force.

The measurement of damping and frequency can be made at any point in the elastic range because the flexibility ratio (displacement per unit force) is a constant in that range notwithstanding the non-linearity of the individual parameters. There is one proviso – damping characteristics at very small amplitudes of response have some additional non-linearities caused by interaction with other structures or b soil/structure interaction, and so the values must be taken from amplitudes at which the flexibility becomes constant.

The expected values of damping and frequency are well defined [4,5], and have subsequently been used in the International Building Code used in the USA [6] The expected value of damping is based on a stick-slip mechanism rather than viscous dashpots and allow the use of fracture mechanics for the interpretation of the non-linear damping characteristics.

There are also implications for engineers from different disciplines because the assumption of a stick slip mechanism allows the following:

1. The stick/slip mechanism predicts values of damping used in wind and earthquake engineering and can be used for predictions of ductility.
2. The stick/slip mechanism allows the prediction of the value of damping at the large amplitudes of response at which the damping value becomes a constant.
3. The stick/slip mechanism implies that damping will start off at a small value and will increase with increasing amplitude. The rate of increase is dependent on the

materials used, the geometry and any attachments to adjacent structures.

The traditional disagreements between wind and earthquake engineers about appropriate values of damping can be resolved by using this holistic description of the damping characteristic. This can be epitomized using a three-part curve for its description:

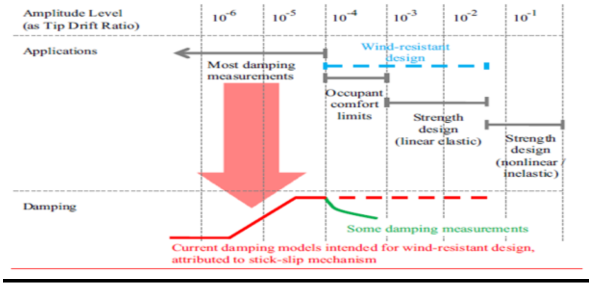


Figure 1. Non-linear damping characteristic.[4]

This holistic damping characteristic shows a classic first mode non-linear damping curve, which can be modified by materials, damage, and geometry in particular.

This characteristic shows that even as a large force is about to affect a structure, the damping value is small and only increases at greater amplitudes of response, or when a structure is damaged. Under such a circumstance the response of the structure will rise to a greater response amplitude faster than is conventionally assumed when an invariant value of damping is used. This effect is greater when the response amplitude is larger [7].

The damping is more variable than the frequency and is much more difficult to measure. However, an accurate measurement of these two parameters can be used to establish the flexibility of the structure at the time of measurement, and a comparison with the flexibility required by code can be used to give the risk ratio of how the structure behaves with what is expected by codification.

This risk ratio can then be used to calculate the return period of an event that would take the structure out of the elastic range, and the return period of such an event as well as the annual probability of such an event.

The techniques can be used for other types of structure as well. Their use with bridges is quite straightforward although the quantity of measurements is much smaller and leads to a wider confidence interval. Clearly more research is needed, but this is made more difficult of the much lower fundamental frequencies of longer span bridges.

6 COMPARISON OF INTEGRITY GLOBALLY

The risk ratio for buildings in various parts of the world has been assessed, using a base of the expectations in the local code of practice. This allows the assessment of global populations of buildings, but only in cases where the precision of measurement and analysis techniques is guaranteed.

The following diagram shows the risk ratio taken from a series of different locations. These are:

1. The gold standard induced vibration tests (all UK)
2. Buildings in New Zealand
3. Buildings in Japan
4. Buildings from all parts of the world (many from the USA)

Each dot in Figure 2 represents the risk ratio for a single building.

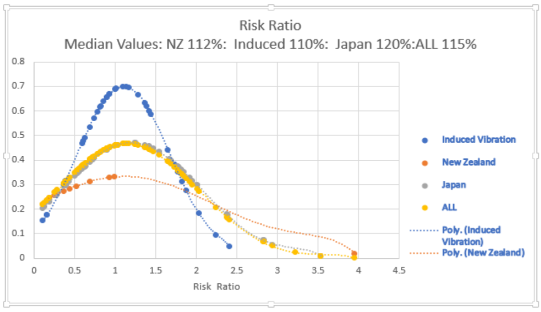


Figure 2 Risk ratio value for a variety of locations

A value of 1 for the risk ratio represents a condition in which the building just meets the minimum requirements of the local code of practice. It is not surprising then, that the median values in all locations are between 10 and 20% above these minimum requirements. What is surprising is that a large number of buildings have a risk ratio of less than 0.5 and considering that most of the surveyed buildings are in first world countries then Figure 2 speaks to a world-wide problem with significant numbers of buildings.

The risk ratio could be used as an indicator for when a building is in such a state of disrepair that urgent action is required. A rule of thumb (based on New Zealand criteria) suggests that a measured risk ratio (approximately 0.8) that results in a return period of 12.2 years for an event that causes the structure to exit the linear elastic range, requires urgent attention.

7 MODE SHAPE CRITERION

If the mode shape of the first sway mode of a building is that assumed in the original design, then this reflects a standard displacement with a maximum at the top of a tall building. The stiffness of the entire structure integrates to form a holistic modal stiffness in which the elements contribute their stiffness multiplied by an influence function that increases linearly with height. However, in some cases the structure has stiffness anomalies in which an area has lower stiffness. In such a case then a mode shape anomaly can occur in the early stages of degradation. Figure 3 shows an example of this.

In the particular case of the building in Figure 3 a broken structural member (as a result of earthquake action) was found after this structural weakness was reported and façade panels were removed for an inspection.

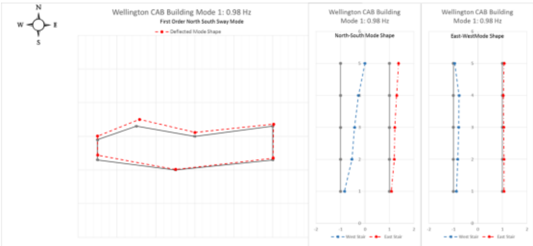


Figure 3. mode shape for a five-story building showing a stiffness anomaly.

In the structure's spectral response, it is sometimes possible to observe a bifurcation in a mode of vibration. Under these circumstances the bifurcation is caused by a small part of the structure attempting to become 'independent' and potentially to break away from the main structure (partial collapse). An example of the effect on a spectrum of the early stages of a cladding panel detaching is shown in Figure 4.

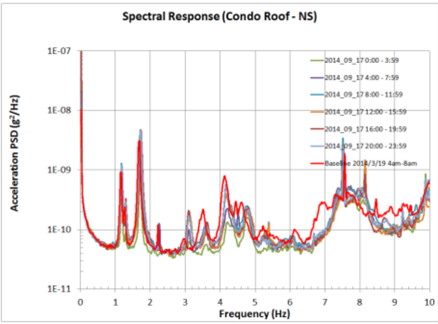


Figure 4 Modal Bifurcation

8. RECENT CHANGES IN LAW USHERS IN A NEW 'STANDARD OF CARE'.

In June of 2022, both Florida and New Jersey have moved legislation forward increasing the inspection cycle for buildings. This was driven by the collapse of the Champlain Tower in Surfside, Florida that occurred in June 2021. This collapse highlighted the fact that all structures are degrading and that owners need to verify that the structures are structurally safe, The Law specifically requires engineers to verify structural integrity of the buildings. These unprecedented new laws change the landscape for asset management. Owners had traditionally been averse to quantifying structural problems and were not forced to address degradation of structures in any way other than with a visual inspection.

Since most structural elements in buildings are hidden, any verification of the structural system for an existing building is likely impossible, if members and connections are not inspectable. Therefore, engineers are put in an untenable position to verify the structural integrity with no way to actually do it. Only through physical measurement can such a verification of integrity, and capacity be made. And that measurement must include the non-linear response characteristics of the structure which relate directly to the structure's capacity, and that which is directed in the codes of practice.

9 CONCLUSIONS

The risk ratio can be used to establish whether a structure performs to a standard required by code. To effect this, measurements of damping and frequency of the first sway mode of a building are used. For bridges, it is the first bending for spans, or first lateral mode of piers.

This allows the estimation of a force that will take the structure to the end of linear elastic behavior and can be used to calculate the return period of an event that will cause this condition.

Additionally, stiffness anomalies in the mode shapes associated with the building's response have been used successfully to identify areas in full scale structures in which severe damage has occurred.

Armed with a model of damping that is based on fracture mechanics (the stick/slip model), then the elastic behavior can be extended to imitate ductile behavior when the structure is subjected to greater forces (such as those caused by earthquake action). Changes to the measured non-linear amplitude-dependent parameters of frequency and damping provide an accurate insight into the reduction of capacity of any structure.

Ultimately significant changes (or small values) of the risk ratio will help identify structures in distress and with the potential of collapse.

The approach outlined in this paper shows how the use of the risk ratio can be used for buildings under both wind and earthquake actions, subject to the effects of aging as well as for all bridges. **The use of a risk ratio should be integrated into a regular inspection cycle for all structures providing the most accurate and scientifically valid verification of damage.** Current methods of visual inspection are extremely limited. As society progresses and structures age, then the verification of structural stability and integrity is now the new Standard of Care.

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