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What can we learn from Structural Health Monitoring (SHM)? Part 2: Case Study

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ABSTRACT

This paper is the second and final part of the series. This part presents a case study of the theory presented in Part 1 (Smith, 2024a). A quantitative analysis was conducted on the data produced by the Structural Health Monitoring (SHM) system installed on 1 Soho Place, a 10 story building in London. SHM data consisted of measurements of the displacement of elastomeric bearings under the columns during construction of the building. The load was then inferred using the stiffness of the bearings. These loads were then compared to the predicted values calculated by the design consultant using linear elastic finite element analysis (FEA). The total load measured was within 10% of the predicted value. The overall correlation between the predicted and measured values was strong (Pearson's r-value 0.907). Although the total load measured was close to that predicted by the FEA, some differences were observed between the distribution of the measured load compared with that predicted. Further, some differences were attributed to measurement system error. The overall difference was then quantified by the variability, found to be much larger than the assumptions assumed within the Eurocodes. System Distribution Factor (SDF) is introduced to separate the load distribution effects from the assumed statistical variability. This exploratory study has presented a method showing how SHM in conjuncton with reliability and Bayesian analysis can be used to modify factors of safety through increased certainty and that elastomeric bearings proved to be suitable for inferring load.

INTRODUCTION

This paper is Part 2 of a 2 part series titled *What can we learn from Structural Health Monitoring (SHM)? Part 1: Theory* (Smith, 2024a) introduces and explains the theoretical basis, and this Part 2 is a case study from a building in London. The SHM data used as the basis for this case study was collected at the 1 Soho Place development at Tottenham Court Road, London. At Soho Place, the measured displacement (mm) of elastomeric column bearings of known stiffness, was used to infer the structural forces (loads) (kN) under the columns. These measured forces have been compared to those predictions derived from the Finite Element Analysis (FEA) (mathematical structural analysis calculations) to understand the building loads and distribution of forces. This study was a quantitative assessment of building Structural Health Monitoring (SHM) data to improve design efficiency using reliability and Bayesian analyses. This experimental method was chosen because to assess the structure's design efficiency, the loads must be measured and then evaluated against the predicted values. This research is also an exploratory analysis to see if elastomeric bearings can reliably infer load from a building.

Site Description

Soho Place is a 10 story mixed-use development on the corner of Oxford Street and Charing Cross Road in London. The development includes 209,000 sq ft of office space, 36,000 sq ft of retail areas, a 40,000 sq ft theatre and new public realm (*Derwent London, 1 Oxford Street*, 2020). The site is located directly above Tottenham Court Road underground station, and the client was Derwent London.

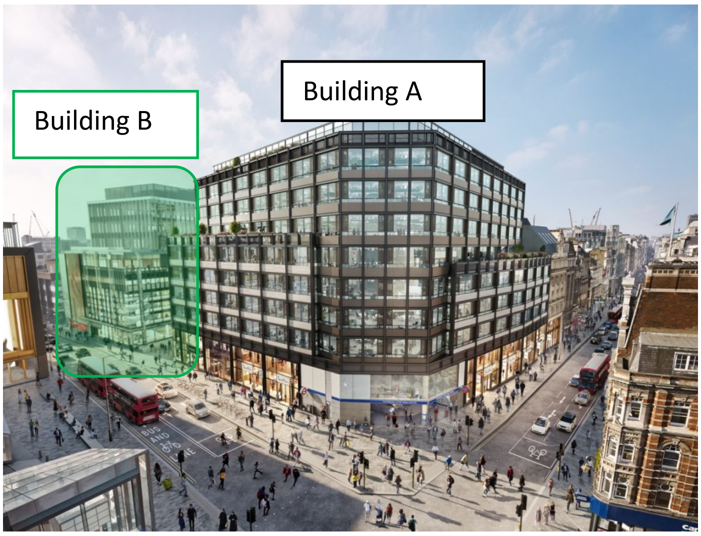


Figure 1 – Architect's Impression of Soho Place. Building B is shown highlighted in green

The site consists of two separate sections, known as Building A and Building B. Building B is the subject of this study and is highlighted in the green square in Figure 1. The steel frame of Site B is a complex statically indeterminate structure that relies on moment frames for stability; this means that the final distribution of load through the structure is dependent on the sequence in which it is built, making a staged analysis necessary. In addition, a number of the columns were founded on top of the Tottenham Court Road underground station box. The load in these columns was monitored to prevent overloading causing damage to the station box. A comprehensive load monitoring regime was specified as part of a risk mitigation strategy to ensure that the actual structural loadings did not exceed the limits established by the underground asset owner. This research was an extension to this specified requirement.

The following Figure 2 is the structural model of Building B. The existing underground station and vent shaft are shown in yellow. The floors are cast insitu reinforced concrete slabs and the walls are either blockwork or precast depending on the location and design requirements. There are 62 bearings; 56 elastomeric and 6 spring loaded. Due to cost constraints, only 48 of these bearing positions were measured by the SHM system. The locations of the sensors measuring the compression in the bearings are shown diagrammatically at the column bases in blue and green.

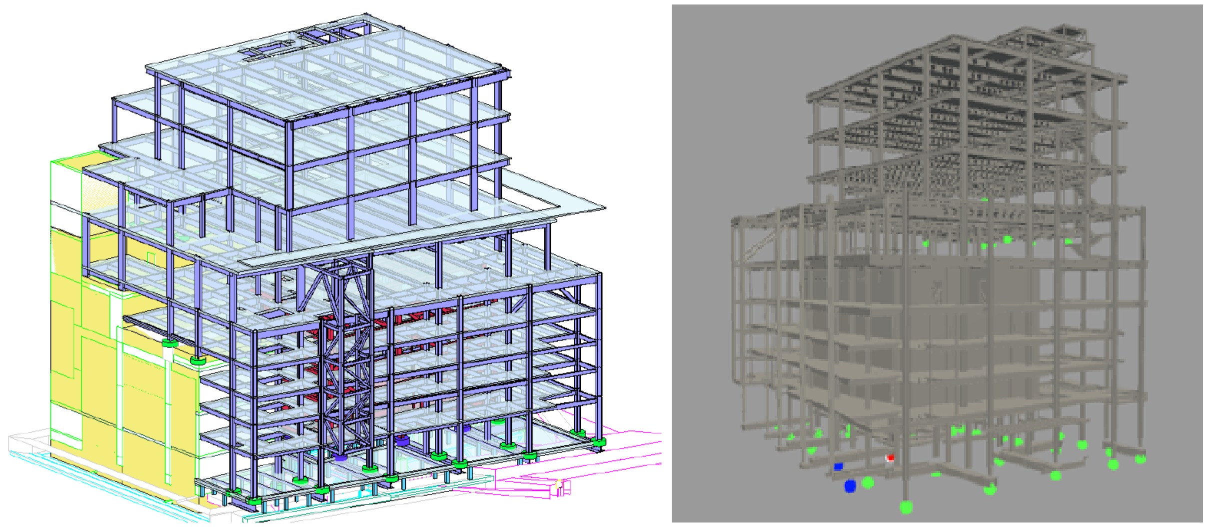


Figure 2 - Building B Structural Model and Locations of the Sensors

Prediction of Structural Load

The predicted loads were based on a structural analysis specifically designed to be used in conjunction with the monitoring regime, these predictions are not the design loads. The design load is a value that contains many different load cases. The design load would be legitimately different from these predicted values solely calculated to compare to the monitoring results. Yet, the predictions are an indication of the accuracy of the FEA.

The engineer used Oasys GSA 8.7 to carry out a first-order linear-elastic finite element analysis (FEA). The building geometry was reproduced from the global structural model. The building was founded on the underground structure that included; a concrete vent shaft and steel trusses below the base slab of Soho Place. The model included the underground structure because it impacted the distribution of load through the steel frame. The tools in GSA were used to subdivide the analysis into various construction stages. Actions due to construction live load, and specific elements of the building fit-out were assigned to the appropriate stages based on the construction programme. The engineer then applied intelligence to sensitivity ranges for a number of these parameters. Finally, they used a spreadsheet to post-process the results from GSA and calculate the upper and lower bound predictions for the column load at each monitoring location.

Because the structure is statically indeterminate, the individual connection stiffness affects the load distribution. The base analysis assumes that all connections are fully fixed. The sensitivity analysis has considered all steel sections had a second moment of area (I) reduced by 20%. Each stage was analysed only with that additional load being applied at each stage to capture the effects of "locked-in" stresses due to the sequential erection of the structure. The predictions represent a best estimate based on an intelligent range of expected values of the input variables. The FEA is based only on the self-weight of the structure as well as any fit-out items installed by that stage. For the purposes of this research, the best estimate was used in all calculations. This value does not include any contribution from construction live loading.

Most of the columns had elastomeric bearings installed at the base to prevent the vibrations from the underground trains travelling up into the structure.

Figure 3 is a drawing of an elastomeric bearing. These bearings are a factory produced element and their stiffness has been well established using laboratory testing. Given that the stiffness is known, the load on each column can be determined by measuring the compression in the bearing, which is observed as a change in displacement.

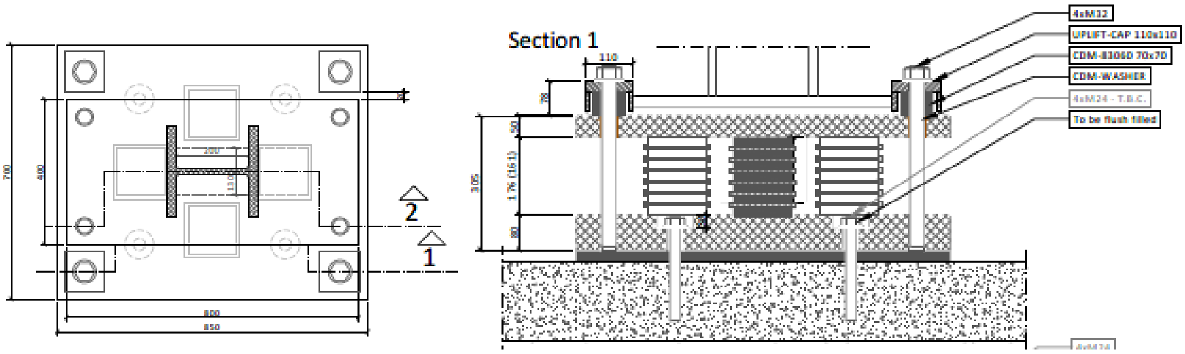


Figure 3 - Drawing of an Elastomeric Bearing

Instrumentation and Monitoring

In order to measure the compression in the bearings, readings were taken using Optical Displacement Sensors (ODS) and then checked using steel vernier callipers. ODS were attached to the top plates of the bearings using magnetic brackets. The sensor had a resolution of 0.1mm and repeatability of ± 0.15mm. As well as displacement, the sensors also measured tilt angle and temperature, which provided a mechanism for correction.

It is very unlikely in a construction environment that any system could achieve an accuracy less than 1mm. But, for this research, the measurements will be reported to the nearest 0.1mm. The maximum deflection measured was 18.5mm corresponding to an inferred load of 564kN and the minimum was 4.5mm corresponding to 78kN.

The ODS were powered by batteries with enough life to provide two years of monitoring based on the proposed frequency of readings required. Assuming the sensors were not disturbed, then access was not required after installation. The battery life was dependent on the frequency of readings taken; more readings require more power and vice versa. The proposed sampling frequency was daily. The sampling frequency could be adjusted remotely to enable further experimentation. For example, the sampling frequency might be increased for a short period to say hourly readings to understand temperature effects over a 24-hour period and then reduced again to daily readings to conserve battery life. The data collection was terminated on 4 June 2020 when the structure topped out.

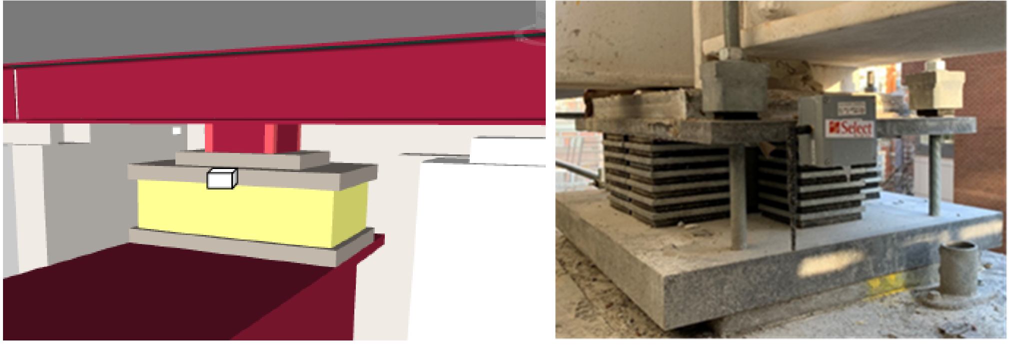
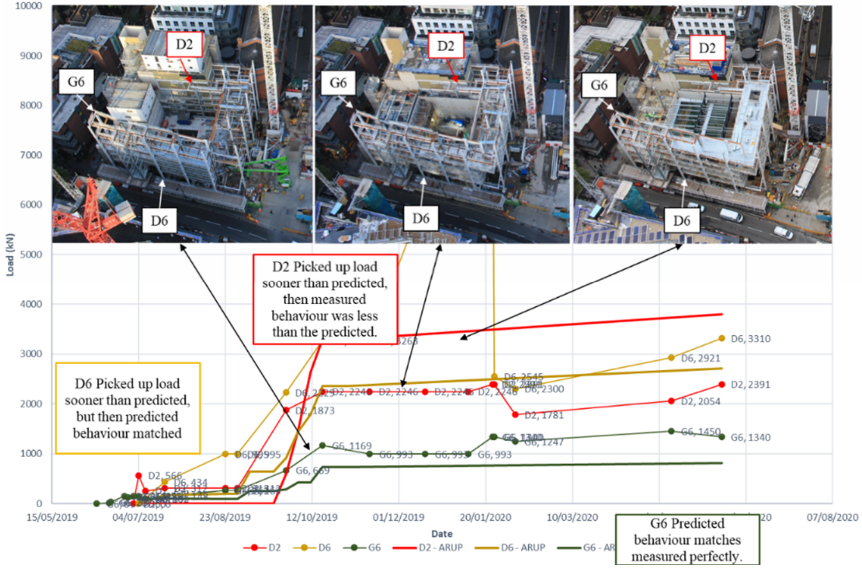


Figure 4 - Digital image and Photograph of an Optical Displacement Sensor (ODS) on the top plate of a bearing under a column

Preliminary Results

Figure 5 shows the preliminary results used to check the SHM measurements against the predictions. The SHM results from the early stages of the construction were studied against the predictions. Figure 5 shows the results from the three heaviest loaded columns (D2, G6 and D6). The measurements, represented by the markers with the thin line, fell approximately along the predictions represented by the thicker graph lines.



D2 Picked up load sooner than predicted, then measured behaviour was less than the predicted.

D6 Picked up load sooner than predicted, but then predicted behaviour matched

G6 Predicted behaviour matches measured perfectly.

Figure 5 - Preliminary Results With Aerial Images Showing the Stages and Load Progression

Final Measured Deflection and Inferred Load

The load distribution was assessed using the SHM data and compared to the predictions derived from linear elastic FEA. The total load measured of 44,644kN was 9% lower than the predicted value of 48,653kN. However, this error is acceptable given the accuracy of the measurement system and is mainly attributed to the calibration of the bearing stiffness. Further, ther was a strong positive linear correlation between the measured and predicted values as indicated by the Pearson’s r-value calculated at 0.907. Therefore, it is conceivable that the measured values might be broadly correct.

The main disagreement between the measured and predicted was the load distribution, revealed by the high standard deviation of the measured/predicted values. This result indicates that a significant finding from this study is that the mathematical models may struggle to replicate the load distribution in statically indeterminate structures. This revelation is not new and is in line with the findings from Baker (1954).

In **Figure 6**, the red circles show the potentially overloaded columns using a simple difference between measured and predicted. Positive numbers (orange circles) highlight any potentially overloaded columns, this is where the measured result is higher than the predicted. Regarding the difference between the loads measured and predicted, two areas were identified where individual columns were potentially overloaded, and these have been shaded red. However, in all but two groups of columns the adjacent columns are underutilised, so the column group capacity is sufficient. By overall inspection of the column groups shaded in green in the building footprint shown in **Figure 6**, the load approximately goes where the designer predicted, but not precisely down the expected column.

Figure 7 presents the inferred load from the bearings divided by the FEA calculated load as a percentage. In this case, values greater than 100% represent potentially overloaded individual columns. When considered in terms of column group utilization (measured/predicted), only one group of columns is overutilized, with a result of 130%. Coincidentally, this is surprisingly close to the 1.35 design partial factor of safety for dead load.

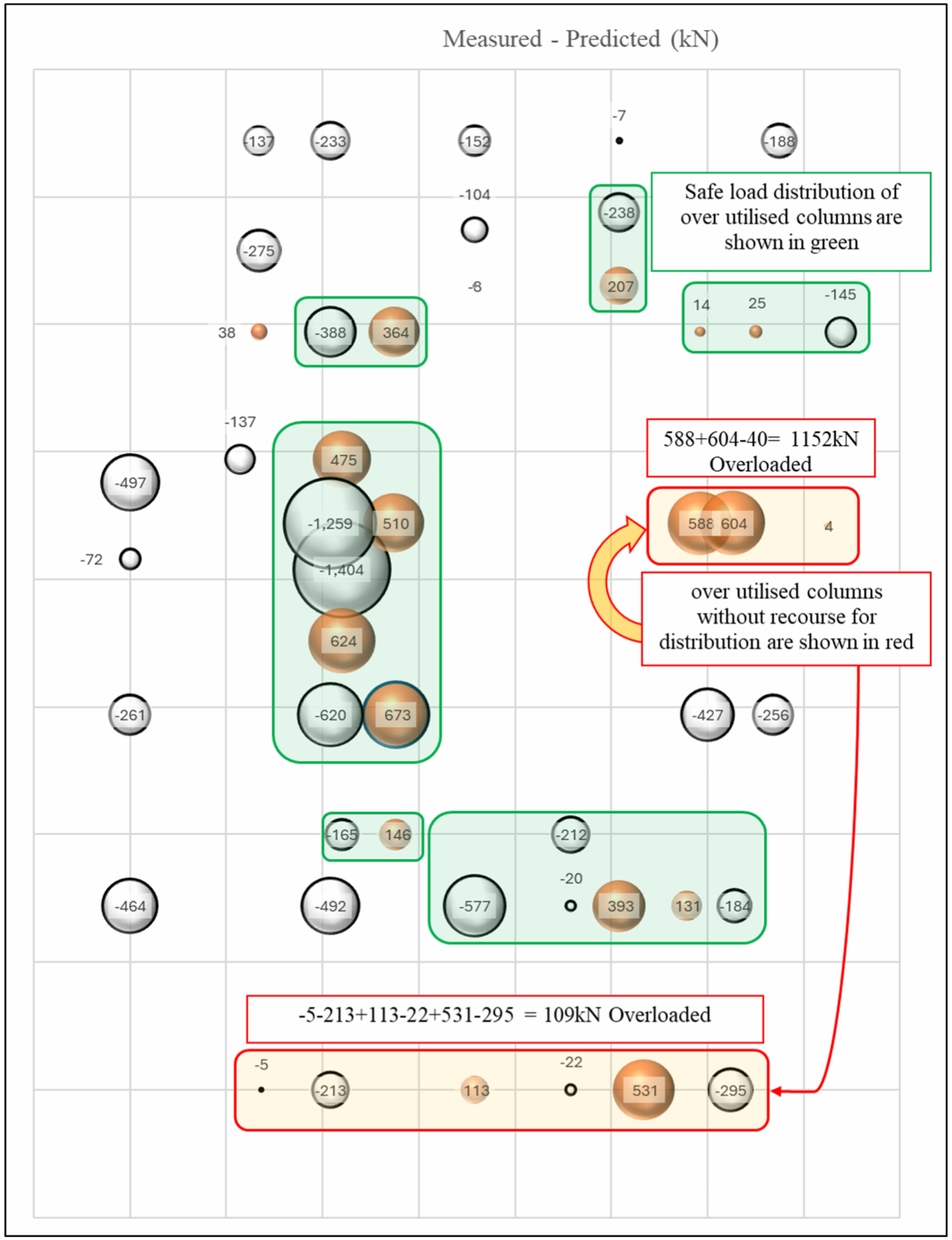
It is important to note that these predictions do not constitute design values. The design values are what might conceivably happen and are likely to be a lot higher. However, considering the partial design factor of 1.35 applied to the dead load, this overutilisation is acceptable from a design risk perspective.

Live load from occupants was not observed using the SHM. However, as this study occurred during the construction phase, this result may be different during the operational life of the building. Typically in the literature, SHM systems consisting of strain gauges rarely detect live loading as the imposed strains are not high enough to be measured by the gauges. To assess live loading, mobile phone or some other physical tracking technology may need to be considered.

This study has highlighted that in applying the ultimate limit state load combination of 1.35G +1.5Q, designers are doing three things;

1. They are allowing for uncertainty of the load,
2. They are allowing for the uncertainty around how the structural system distributes the load, which is still somewhat unknown, and
3. Making some allowance for gross errors during construction

The dead load itself is straightforward to calculate, especially with precast or prefabricated components, or even by surveying exact measurements of cast-in-situ components. However, it seems that despite advances in computing and modern methods of construction, there is still much uncertainty about how this dead load is distributed from the roof down to the foundations, especially in statically indeterminate structures, and the results have clearly shown this.



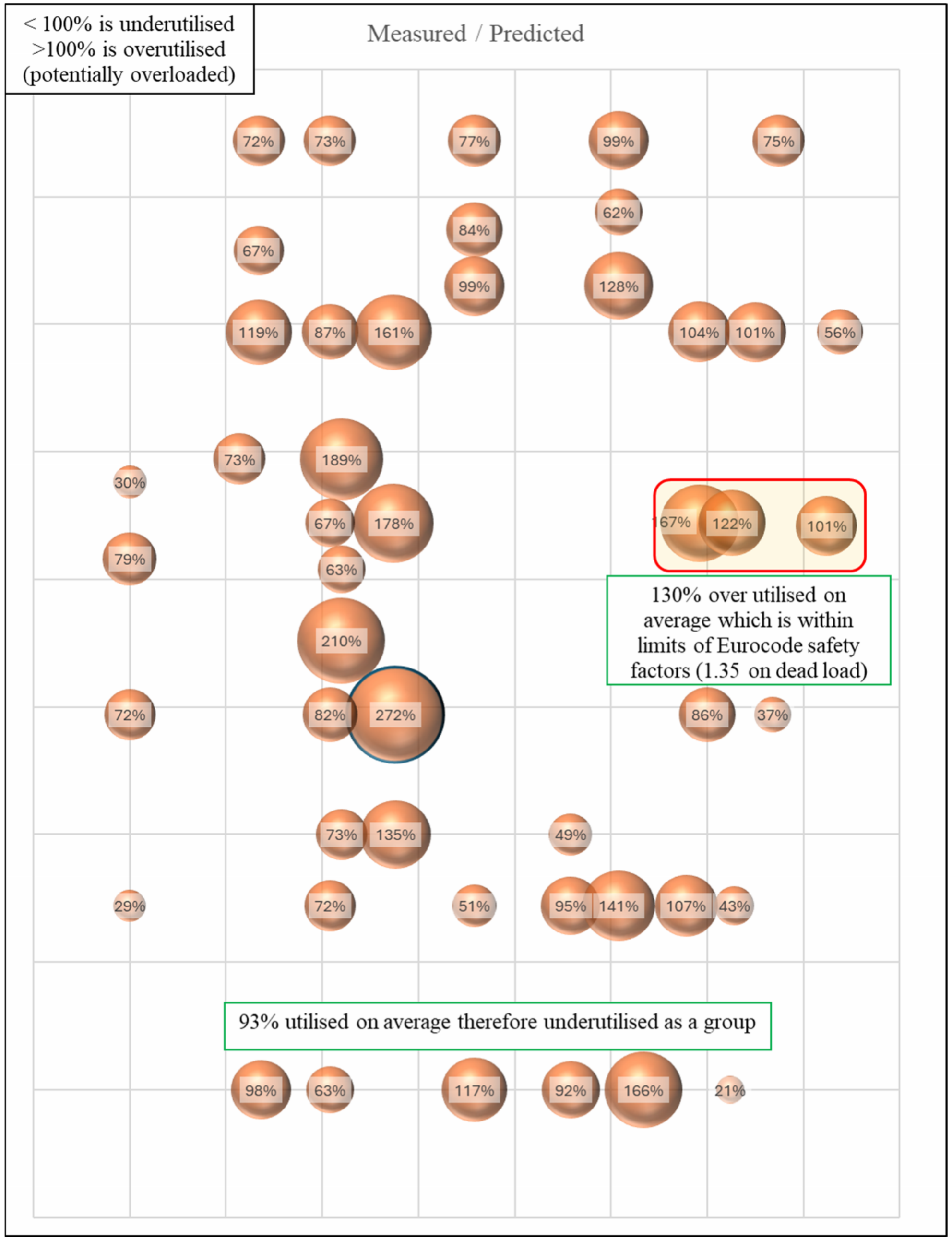
Safe load distribution of over utilised columns are shown in green

588+604-40= 1152kN Overloaded

over utilised columns without recourse for distribution are shown in red

-5-213+113-22+531-295 = 109kN Overloaded

Figure 6 - Measured Load minus Predicted Load (Difference)



< 100% is underutilised
>100% is overutilised
(potentially overloaded)

130% over utilised on average which is within limits of Eurocode safety factors (1.35 on dead load)

93% utilised on average therefore underutilised as a group

Figure 7 - Measured Load divided by Predicted Load

Reliability & Bayesian Analysis

Figure 8 presents the SHM results with the research target presented in the top graph with the results below. When comparing the research target to the SHM results, it is essential to note that the yellow distributions representing the Eurocode assumptions are the same curve, but the graph scale is entirely different. This discrepancy is due to the vastly different values for variability. in Figure 8, the target variability of 0.0188 corresponding to a factor of safety of 1.05 can be compared to the measured variability of 0.493 corresponding to a factor of safety of 2.31. The targeted high degree of certainty shown by the green distribution in the upper graph, has unfortunately not been achieved.

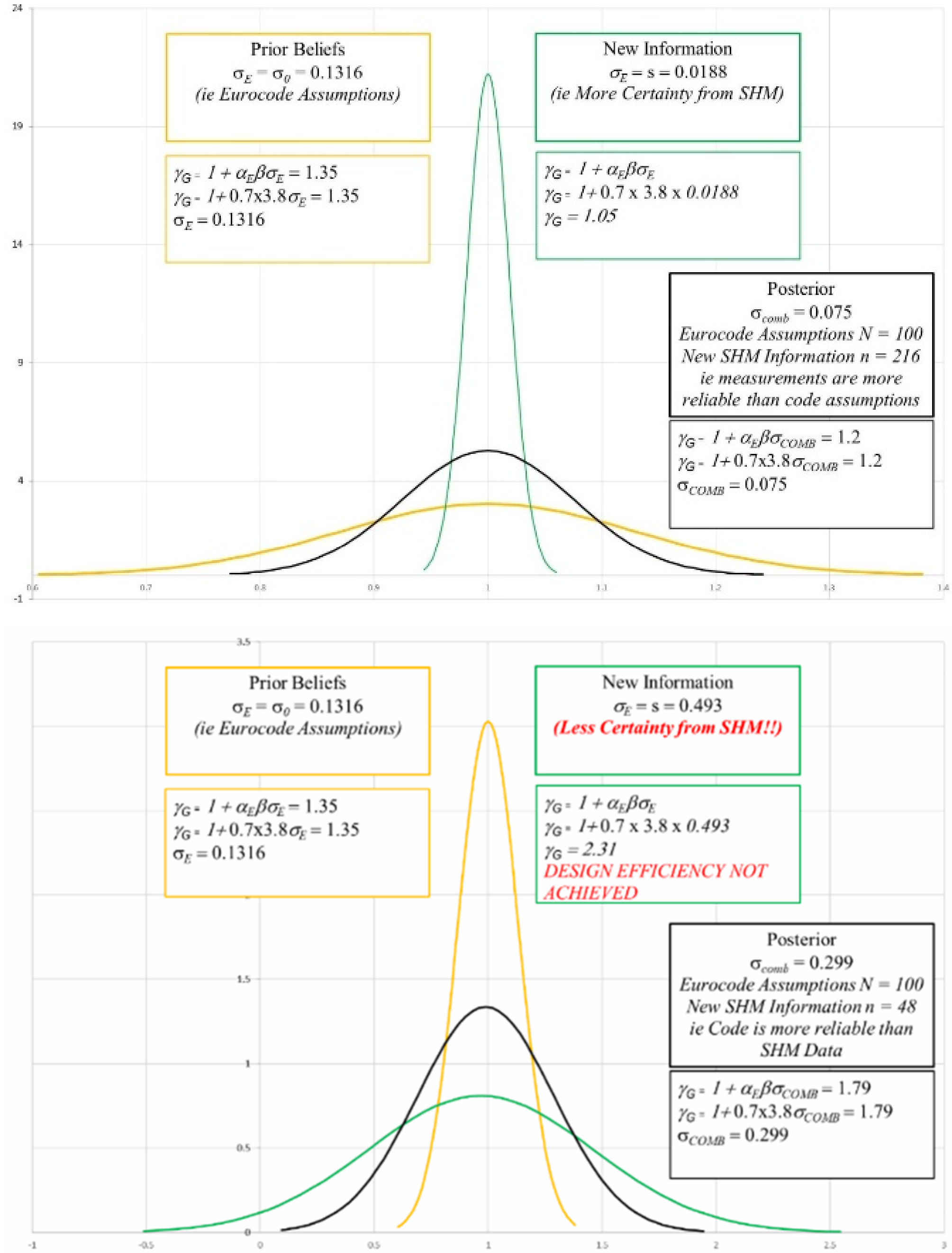


Figure 8 Research Target on the Top and Results Below

Conclusions

This research set out to investigate how Structural Health Monitoring (SHM) could be used to improve design efficiency and to reduce embodied carbon through more efficient material usage. This research built on top of a wealth of existing work, but then extended this knowledge by presenting a method to utilise SHM data in reliability and Bayesian analyses to design Eurocode partial factors. This research has shown that it is practically possible to use elastomeric bearings to infer load as part of an intensive SHM system in a construction setting.

Using a similar approach, for a refurbishment or as part of building commissioning, the load distribution could be measured using SHM in combination with a proof load test by water filled bladders. This method could also help the steel industry to justify lower material design factors through a comprehensive SHM study of a steel-framed structures, given strain gauges applied to prefabricated steel elements produce highly accurate measurements of the inferred load.

The main conclusions are summarised as follows:

SHM Reliability and Bayesian Analyses – Partial Design Factors

This research has presented for the first time a process of incorporating SHM data as part of reliability and Bayesian analyses to calculate partial design factors. Unfortunately, there was much less certainty provided by the SHM data when compared to the Eurocode assumptions, theoretically the partial design factor increased. The research target was not achieved. Although the approach and the method were sound, the SHM did not provide any greater certainty, so the partial factors were not reduced, and no surplus capacity was given back to the owner for future expansions. If it was possible to improve certainty using this method and better the Eurocode assumptions, then the partial factors could be justifiably reduced. If using the results were a step too far, Bayesian combining could be used to nominate an appropriate middle ground. In the long term, as this approach becomes more widely adopted throughout the industry, reducing partial factors may be more easily justified while maintaining appropriate structural reliability levels.

The way probabilistic design methods treat the ‘unknown unknowns’ needs significant consideration. The true probability of failure of structures is much higher than their designed value, in some cases by about three orders of magnitude. This is because most failures occur due to “gross error” rather than being at the tail of a probability distribution. Carelessly reducing safety factors has been referred to as ‘tip-toeing blindly towards the edge’. However, SHM has the potential to better define where that edge lies accurately. Reliability and Bayesian analyses are potent methods of improving design efficiency by calculating revised design partial factors. Using probabilistic methods, the structural designer must shift their thinking from attempting to accurately determine discrete design actions to assessing the uncertainty around each applied load.

This approach would be best applied by consistent Client-Designer-Builder-SHM teams, rather than those thrown together, and to those clients who build multiple similar structures for example, high rise developers. In this way, buildings become less like a prototype and project delivery starts to become more analogous to the aircraft and automotive industries, generating the associated productivity benefits. The benefits of maintaining consistent Client-Designer-Builder teams is in line with many construction industry reports on productivity (Latham, 1994).

Naturally, following on from this study, as more buildings are monitored, a database of design loading information (mean value and variability) can be populated. This database could be used to improve future designs and to assess structural failures. Similarly, using SHM to measure load path and distribution would improve the existing structural analysis mathematical models and help to introduce new low carbon materials as has been observed in other industries. In time, with enough data, it is concievable that Artificial Intelligence and Machine Learning given access to this data could surpass the accuracy of the current structural analytical methods.

Assessment of Surplus Capacity

Once the structural load is measured accurately, it is known, no matter how powerful the computer that carried out any contradictory analysis. Much effort went into explaining why the monitoring at Soho Place was incorrect, but very little into why it might be right. However, suppose the measured load was very accurate, creating a high degree of certainty in the measured values. In that case, post design it could be argued that except for the overutilised column identified, all the columns have a safety factor of at least 1.35 on the dead load. Assuming that the dead load does not change throughout the structure's life, this represents at most 35% of the dead load as surplus building capacity. The designer could compare the (assumed perfect) measurements with the design loadings to accurately calculate the surplus. The difference would represent the surplus capacity, and the building expansion could then be designed. As the new part of the structure is built, the SHM system would remain in place and measure the increase in load up to the initial design values. In this way, the expansion would 'take up the slack' and utilise all the surplus capacity. Concurrently, the designer would need to reanalyse the structure based on the unfactored measured values to improve the imperfect structural analysis model. This would enable continuous improvement and better predictions in the future. However, in reality, how much of any surplus can be given back to the owner is difficult to determine, especially given the building planning controls and insurance aspects to consider.

System Distribution Factor (SDF)

Like all things in nature, it is complicated to create a perfect mathematical model with appropriate assumptions and complexity that is reflective of the actual structure. The basic assumptions a designer makes in structural analysis that determine load distribution are; Load magnitude and variability, Joint fixity (either pinned or fixed), Beam continuity (continuous, simply supported or cantilever) and Element dimensions and stiffness (Young's Modulus – fixed for steel variable for concrete). Even if the structural designers have not made any mistakes, they know their imperfect analysis includes assumptions about how the structure will be built on-site, what loads will be applied, even the ambient temperature and torque at which the bolts are done up, all of which will mean that the measured stresses will not be the same as those predicted.

SDF is a way to separate the uncertainty of the applied loads from the ambiguity of load distribution. Like assigning risk level and β-value, the determination of an appropriate N/n value in between the upper and lower bounds is complicated. However, when the distribution is known for one load type, in this case the dead load, it can be applied to all other loadings on the structure, including imposed and wind loads. Generally, or in complex structural systems, the Bayesian weighting factor N/n should be set at 100, resulting in a design equivalent to the using Eurocodes with the nominated design partial factors - this represents an appropriate upper bound design. However, in simple structures or structures where the distribution can be either accurately predicted or controlled, then this weighting factor could be set lower, towards N/n=0.01, resulting in the lower bound partial design factor of 1.05. This is commonly the characteristic design value and was the original research target. If an SHM system was in place, capable of accurately measuring the load, the variability could be used as the weighting factor and then capped at the upper bound, as was the case in this research. Perfect predictions would yield the lower bound distribution factor. As the building will have been already constructed, this benefit would represent a surplus capacity to be used for future expansion. Using this combined approach, it is foreseeable that the factor on the dead load may reduce from 1.35 down to 1.05 the research target. The cost of the SHM would be minor compared with the material savings and associated environmental benefits.

Limitations and Error

This was a limited study done on a statically indeterminant steel-framed building in London - only one sample from a vast global population. If the study were extended to different types of buildings for example reinforced concrete or timber-framed then the results may be different. Further, various design consultancies and other mathematical models may generate better or worse predictions. At the very least, this approach could be used to check the predictions made by the design consultant. This feedback loop would be beneficial in increasing the skill and expertise of the design community.

The study focuses on dead load only. This restriction may appear to be imprecise. However, live loading was not measurable in any of the case studies identified in the literature because it represents a minor part of the total load that determines the design of the columns, so much so that the strain caused by the live loading was so small it was not measurable by the sensors. Similarly, live loading was not observed in the SHM data on this project. Finally, the construction live loading assumed in the FEA was similarly a minor contributor to the total load predicted. So this approach was deemed to be appropriate. Assuming live load could be measured, then this methodology could also be applied. As opposed to SHM, occupancy levels and in turn imposed loadings could be better determined using registered mobile phones or building access passes.

Sources of error include the SHM measurements, bearing load-stiffness calibration and creep of the elastomeric bearings. All of these are by their nature, are difficult to quantify. Techniques to reduce the error have been discussed. Load cells could be used to obtain better measurements. Alternatively, strain gauges attached to steel members with accurate modulus and dimensions would infer load with greater accuracy.

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BIOGRAPHY

Ben is a Technical Director, professionally qualified in both the United Kingdom and Australia, with extensive experience in providing engineering analysis & design and construction management across fast-paced environments. Ben has been fortunate to have had a distinguished career in the industry, leading the design and construction of iconic projects, across a number of sectors, both in the UK and internationally.