Machines for living – true performance-based design

Pete Winslow
MEng, MA, PhD, CEng, MIStructE
Associate, Expedition Engineering, London, UK

Synopsis
Are codified serviceability and stiffness criteria appropriate in a world increasingly focused on reducing material use and embodied carbon? Could new approaches to loading and movement offer ways to meet these goals? Does modern technology create the potential for adaptive designs which actively control deflections? This paper explores ways in which the structural engineering profession could move towards a truly performance-based design approach, drawing on examples from the work of Expedition Engineering and other engineers.

Every engineer knows that we need to design safe and usable structures. First, this means using sufficient material for strength and stability, i.e. satisfying the ultimate limit state (ULS) – be it in steel, concrete, timber or some other material. The second fundamental principle, and one which appears in all modern design codes, is to design structures that are stiff enough, i.e. that satisfy the serviceability limit state (SLS), so that they don't move or deform 'too much' under some statistically calculated characteristic loads.

But in many cases, this traditional approach to serviceability and stiffness needs far more material to be added than is required just for safety. Is this overkill for real-world situations? Are there better ways of achieving the required performance? Is $L/250$ really a good proxy for usability?

With a trend for higher-strength (but little stiffer) materials, longer spans, more slender structures (Figure 1) and a drive for reducing embodied carbon wherever possible, it is becoming increasingly important that we, as a profession, tackle these questions. In fact, I believe that the simple first step is to ask these questions on every project, and to develop an ethos of 'doing better than last time' on every project; not just the privileged few that are publicised at the Structural Awards and in *The Structural Engineer.*

One doesn't have to look far to see some obvious situations where we should challenge the approach to serviceability movements, and instead look at the true performance requirements. Consider the football stadium structure which only really needs to meet stiffness requirements for 90 minutes once per fortnight, or an office floor which, in reality, only sees a fraction of the characteristic design load. These are the types of applications where, in my opinion, thinking based on first principles and a research approach to problem solving would complement existing efforts to bring about a new paradigm for performance-based design and material use.

Over recent years at Expedition we have started to think about a number of the underlying principles and how to tackle them differently. These fall into three broad areas in which we look to:

- challenge statistics on loading
- control movement in new ways
- relax serviceability criteria; or 'let it move'.

Figure 1
Dune Grass by Atelier One[1]; high-deformation structures that still meet ULS requirements

Figure 2 6m long adaptive truss structure, IASS Amsterdam EXPO

EXPEDITION ENGINEERING

Challenge statistics on loading

The example of challenging office floor loading is interesting to explore. This has been the repeated focus of many different practitioners and academics over the years – starting with Dunham[2] in 1947, Stanhope[3] in 1992 and 2004, Alexander[4] in 2002, not forgetting Chris Wise's IABSE Milne Medal Lecture[5] in 2010 and, no doubt, others since – seemingly with little impact on the majority of built projects. However, this work has tended to be principled truth-seeking, i.e. determining 'real' loads.

Challenging and changing the accepted norm for applied loading is easier if we focus on optimising the design for serviceability only, rather than for all conditions. For the moment, let's park the idea of changing loading for ULS (since a large body of precedent indicates that current approaches are, in general, very safe). This pragmatic focus on SLS loads is where we should take a path of least resistance.

In a sense, there are two aspects to challenge:

- an accepted norm where many clients value floor capacities in excess of the Eurocode-specified 2.5kN/m^2 + partitions
- a failure to implement the research which shows that even 2.5kN/m^2 is excessive for real offices.

It is worth noting that, although in some isolated cases the use of higher floor capacities arises from careful thought (e.g. if a change from office to retail use is assessed as likely in the future), anecdotally this is mostly not the case. Even if a future change of use is deemed a significant possibility, given the likelihood of incorrect predictions, a more refined approach should be developed. This would involve strategically reinforcing components which are easy to modify now but will be hard to modify in future (e.g. foundations, columns, key connections), and designing other elements (e.g. beams, slabs) just for loads required today while checking there would be space available for strengthening should it be required in many years' time.

Clearly, other types of loading can be challenged in a similar manner, be it snow, wind, thermal, etc. For example, it is very often the case that site-specific wind tunnel testing gives design wind pressures lower than the code. Since it is not practical to use sophisticated physical testing methods on every project, could this not be fed through

> **"THERE IS AN OBVIOUS ADVANTAGE AS REGARDS FLEXIBILITY OF USE TO DESIGN THE BUILDING SO THAT THESE MAXIMUM LOADS CAN BE PERMITTED ANYWHERE. THERE IS JUST AS OBVIOUSLY A LACK OF ECONOMY IN PROVIDING STRENGTH THROUGH THE STRUCTURE THAT WILL NOT BE USED IN 99% OF THE BUILDING"**
>
> **J.W. Dunham, 1947**

into code approaches? In the short-to-medium term this might only really be appropriate for non-safety critical aspects of the design. It would be achieved in practice by using a shorter design life for SLS and accepting that there is a chance of higher deflections, on rare occasions.

This refocus on the SLS loading statistics, rather than both ULS and SLS, would make it easier to get buy-in from project stakeholders. In many cases, it is serviceability which governs the design anyway – be it deflections or vibrations. The Institution's Research Panel now has an 'industry focused' research challenge in this broad topic area[6], and we'd love to hear from people interested (whether or not they are applying for a seed grant).

However, it is likely that even the most creative technical research on loading statistics will still only go some way towards actually delivering value to the client and to society in general. Technical studies need to go hand in hand with socioeconomic studies. Perhaps engineering institutions and funding bodies should embark on a programme of understanding and enlightening clients, developers and letting agents (often cited as a significant barrier to reducing loading allowances for offices); a Class A office can still be achieved even when the load allowance is substantially less than 4 + 1kN/m^2! We should focus on demand-side changes – in much the same way that the climate-change/sustainable energy debate has for some time – to reduce our resource use while still achieving appropriate performance.

Control movement in new ways

Other fields – be it automotive, aerospace, or the natural world – do not simply throw more 'passive' material at a problem to control movement. With 21st century technologies in sensors, control and actuation, active control has real potential. Expedition has been collaborating with researchers Dr Gennaro Senatore and Dr Phillippe Duffour at University College London to investigate adaptive building structures[7]. In addition to technical papers – which have their place but, I have found, rarely initiate real change in practice – a significant outcome is a large interactive prototype adaptive truss (Figure 2).

This 6m long cantilever with an incredibly slender 40:1 length-to-depth ratio is sized for ULS using high-strength steel. For controlling SLS movements it then uses a network of strain gauges, a sophisticated control system and 10 fail-safe electric actuators. The actuators, embedded within the diagonal tension elements of the truss, shorten or lengthen to ensure overall deflections remain less than 2mm as a person walks along the catwalk-style cantilever structure.

This technological performance-based approach can actually go further still: the passive steelwork is carefully designed so as not to deflect excessively under small (frequent) loads. The actuators only need to move occasionally, when higher loads occur, thereby expending minimal electrical energy over the whole life of the structure. In practical terms for, say, a canopy roof structure, the actuators would kick in for the biggest windstorm of the year, but remain switched off for typical winds seen on a daily basis. The team has shown that, compared to a conventional I-beam cantilever, this can reduce mass by 80% and whole-life energy (embodied plus operational) by 60–70%.

The prototype received acclaim at the International Association of Shell and Spatial Structures EXPO in 2015, and also at the Building Centre, London, in 2016. We hope that you will take forward the ideas and principles in your engineering thinking, R&D and construction projects – more details can be found online[8].

One might reasonably ask whether there are simpler, cheaper or easier ways to achieve the same physical benefits. In the short term, adaptive designs could be applied directly to a small number of hi-tech pavilions and boutique structures where such questions are of secondary importance. In the longer term, we as engineers may well be reducing the environmental impact of our structures in any way possible – something examined in more detail by Giesekam *et al.*[9]. However, from my experience bringing together R&D and design on construction projects, it is likely that our built environment will benefit from this adaptive technology in a manner very different to that first anticipated. All projects should take benefit from the philosophy of decoupling ULS and SLS design and going back to first principles. Some of those projects might benefit from a limited adaptive system; be it a single range finder instead of 200 strain gauges, or a single actuator to adequately control deflection rather than 10 controlling to laboratory precision.

A project where the designer can find synergies would likely realise the largest benefits of adaptive design philosophies. For example, since high-strength steel has the same elastic modulus as regular steel, combining it with adaptive systems for deflection/vibration control will enable it to be used to its full potential. In areas where settlements are a concern, foundations are likely to be subject to surveying/monitoring anyway, so combining with a low-tech movement compensation system would be a relatively small step. Separating SLS from ULS in this way and designing the foundation itself for only ULS conditions could, for example, result in significantly shorter piles, or even small pads instead of piles. To realise this potential benefit, we need research into 'productising' and mass-producing adjustable black box-style devices, for permanent foundations or temporary works (not necessarily a new idea, but typically done only on bespoke one-off projects).

Let it move

Is movement such a bad thing? Do we actually have a good, current evidence base that supports use of deflection criteria such as $L/250$, $L/360$, $L/500$ (which are essentially a proxy measurement of outcome – cracking of finishes, comfort, etc.)? If we made a medical analogy, the National Institute for Health and Care Excellence would tell us that we must conduct trials to determine what outcome is actually required, how it can be properly measured and what cost-effective 'dose' of material is needed to produce a particular as-built outcome.

In addition to looking at serviceability criteria, understanding the financial costs of different levels of SLS loading would be another good starting point. Building to a lower SLS design load and accepting a slightly higher probability of, say, brittle finishes cracking would probably make financial sense, and could be optimised with relatively simple 'reliability analysis' style modelling; encompassing material costs, maintenance costs and load statistics.

A recent project Expedition has been involved in – the Stavros Niarchos Foundation Cultural Centre, Athens[10] (Figure 3) – gives a glimpse of what can be achieved in this area. The long-span photovoltaic canopy structure has a network of novel viscous-polymer springs forming part of its support and stability system, with resulting movements three to four times greater than might conventionally be allowed. This reduces thermal, seismic and settlement-induced loads.

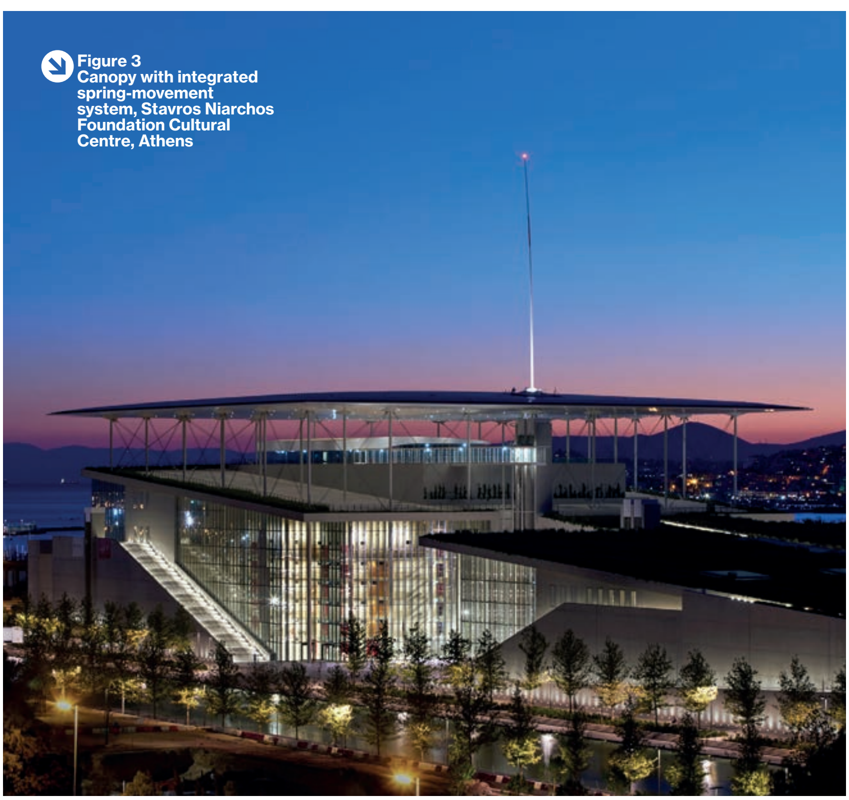
Figure 3 Canopy with integrated spring-movement system, Stavros Niarchos Foundation Cultural Centre, Athens

MICHEL DENANC

Of course, it needed care regarding detailing of the glass-panel photovoltaics, and invention of a special services riser to protect the high-voltage cable from large relative movements between independent structural zones. But the benefit was a significant reduction in material in combination with realising the architect's vision. At present, a system of pressure and displacement sensors is logging to a web server to help the project team to evaluate and learn from real performance.

It is encouraging to see that there is growing interest in this topic area in the academic research community – e.g. it is a major theme of the GW4 university collaboration programme between Bath, Bristol, Exeter and Cardiff university engineering departments.

We, as an industry, should now move beyond doing this kind of thing for just (a) landmark one-off projects or (b) to enable a new class of tall buildings (sexy, publicity-grabbing subjects which make the extra effort more easily justifiable). If the engineering model says that there is a possibility of plaster in my house cracking in a 10-year load event rather than a 50-year load event, does it really matter? Do we know that well-being and productivity in a conventional office space will actually suffer if the vibration levels are, say R=16 rather than R=8? The answer is probably 'not sure', because the construction industry is organised in such a way that far too little post-occupancy evaluation and learning takes place (from a structural engineering perspective at least).

Yes, this can be about cool tech, sensor networks, dynamic movement, research and adaptive systems. But it's also more than that. It's about all of us as a profession challenging traditional engineering philosophies. It's learning how to do things better, towards a truly performance-based design approach which uses finite resources intelligently.

Acknowledgements

Pete Winslow leads Expedition Engineering's R&D initiatives and is a member of the Research Panel of The Institution of Structural Engineers. This article arose out of a request by the Institution's Structural Futures Committee for a contribution on new structural paradigms.

REFERENCES

►1) Calflier001 (2012) *Blackpool Seafront July 2012* [Online] Available at: https://commons.wikimedia.org/wiki/File:BLACKPOOL_SEAFRONT_JULY_2012_(7581633936).jpg (Accessed: February 2017)

►2) Dunham J.W. (1947) 'Design live loads in buildings', *Trans. ASCE,* 112, pp. 725–745

►3) Fitzpatrick A., Mathys J., Taylor A. and Johnson R. (1992) *An assessment of the imposed loading needs for current commercial office buildings in Great Britain,* London: Stanhope Properties

►4) Alexander S.J. (2002) 'Imposed floor loading for offices: a re-appraisal', *The Structural Engineer,* 80 (23/24), pp. 35–45

►5) Wise C. (2010) IABSE *Milne Medal Lecture: Enough is enough* [Online] Available at: http://istructe.adobeconnect.com/p87368980/ (Accessed: February 2017)

►6) Institution of Structural Engineers (s.d.) *Research* [Online] Available at: www.istructe.org/resources-centre/technical-topic-areas/research (Accessed: September 2016)

►7) Senatore G., Duffour P., Hanna S., Labbé F. and Winslow P. (2011) 'Adaptive structures for whole life energy savings', *J. IASS, 52* (170), pp. 233–240

►8) Winslow P. (2016) *A new design philosophy – adaptive structures* [Online] Available at: http://expedition.uk.com/thinking/a-new-design-philosophy-adaptive-structures/ (Accessed: September 2016)

►9) Giesekam J., Barrett J. and Taylor P. (In press) 'Scenario analysis of embodied greenhouse gas emissions in UK construction', *Proc. ICE – Engineering Sustainability*

►10) Frearson A. (2016) *Renzo Piano completes Stavros Niarchos Foundation Cultural Center on a huge artificial hill* [Online] Available at: www.dezeen.com/2016/06/28/renzo-piano-stavros-niarchos-foundation-cultural-center-athens-huge-artificial-hill/ (Accessed: September 2016)

HAVE YOUR SAY

To comment on this article:
►email Verulam at tse@istructe.org
►tweet @IStructE #TheStructuralEngineer