3.Lean design

Lean yet resilient – designing for the future

Caroline Field explores the relationship between 'lean' and 'resilient' design, and discusses how future designs should evaluate risks and incorporate strategies to mitigate and adapt to these.

Introduction
In the future, structural design will face increasingly uncertain loads (we have seen one-in-100-year floods occurring every six or seven years), combined with reliance on engineers and designers to accurately define the parameters that design algorithms will use. At the same time, we are being encouraged to use fewer materials (for a sustainable future) and to adopt lean processes. How do we reconcile these demands? What does the future hold and how do we design for these seemingly competing commitments?

What is lean design?
Lean is the practice of creating more value with fewer resources. The idea of utilising lean principles on a project has gained popularity over the years. The purpose of lean techniques is to make the project more efficient and maximise value.

This issue of *The Structural Engineer* deals elsewhere with the question of what 'lean design' looks like[1], but structural approaches typically come down to delivering 'more for less' to the client. However, given lean is creating value, this can be achieved through better and more collaborative working, rather than just by taking spare capacity out of the structure. For example, working in a more integrated manner to come up with a design that realises multiple benefits.

What is resilient design?
The ISO definition for resilience is: *'The capacity to absorb and adapt in a changing environment'*[2].

In the context of building engineering, this describes the capacity of buildings to withstand short-term hazards (referred to as 'shocks') and be adaptable to longer-term changes (referred to as 'stresses') such as those related to change in use, change in technologies, climate change and changes due to material degradation and lack of maintenance. More resilient buildings are better able to retain their business function through protecting their critical resources.

The level of resilience required depends on the business or community function that the building serves and the tolerable impact that a loss in function would cause. This can be considered as a 'return to service' or 'recovery time objective' and should be agreed with the client.

Design strategies for resilience
There are a number of strategies for building resilience and this doesn't necessarily need to result in increased cost or physical strengthening. It will depend on the risk of the event, the performance requirements of the building and the importance of the building function.

Resilience strategies typically fall into two categories: measures that mitigate risks, and measures that allow adaption to deal with future change and uncertainties[3] **(Figure 1)**.

The risk due to the various hazards (shocks and stresses) can be considered the 'resilience demand' on the system, and the combination of adaptive capacity and mitigation measures can be considered the 'resilience capacity'. The difference in the two provides the performance outcome **(Figure 2)**.

How do we currently include resilience in our designs?
All engineers currently deal with risk and uncertainty in their work, although they may not recognise it. Some examples of everyday risks and uncertainties include material properties, loads, and analytical modelling uncertainties.

Most modern codes are based on a semi-

FIGURE 1: Mitigation and adaptive capacity measures

RESILIENCE CAPACITY			
MITIGATION		ADAPTIVE CAPACITY	
Prevent	Legislation or broader intervention that removes or reduces the hazard/risk, e.g. land use planning to avoid building in flood-prone areas or to permit construction only of resilient buildings.	Provide monitoring systems to identify changes in system demand or capacity. Conduct trend analysis and scenario planning, e.g. monitoring and predicting effects of change.	**Awareness**
Prepare	Development of resilience strategies and plans, including performance requirements for assets.	Build ability to easily upgrade or change systems. Provide flexibility in design to repurpose usage and layout.	**Adaptability**
Robust	Build a system's ability to resist an impact without changing its initial stable form, such as a structure that has been enhanced to withstand specific extreme shock factors, e.g. wind, flooding, blast, heat or dust, where a threat has been identified.	Understand how the building will need to respond/function for different scenarios. Will it need to be evacuated? Provide operational personnel information to inform their response and recovery plans to help reduce the impact of the event and to prevent cascading events.	**Response**
Redundant	Add components which are not necessary to functioning in case of failure in other components, such as utilities in loops, so that supplies can be re-routed to ensure continuity if there is a break or interruption at any point. This could also be alternate load paths in structures.	Design allowing for appropriate return to service time. This should be discussed with the client and will depend on the building purpose and performance requirements. Use local materials to speed recovery (and reduce carbon).	**Recover**
Failsafe	Implement measures to ensure that any failure is proportionate and does not propagate within the system or instigate other undesirable events, e.g. identifying the failure modes of a structure and making sure that loss of one member, or exceedance of design assumptions, does not cause disproportionate or progressive collapse.	Develop methods to capture evidence, learning and innovation.	**Learn & improve**

probabilistic format (reliability method that employs only one 'characteristic' value of each uncertain parameter) – limit state design – which is simpler to codify than higher-order methods and can be easily applied by design engineers. Partial factors keep the probability of failure/exceedance of a structure low, and account for deviations in material and geometry or second-order effects.

By meeting the requirements of a code, a structure is considered to have an acceptably low probability of failure. However, the basis of the entire design is the structural engineer's assumption of the actions/loads the building will be subjected to during its lifespan. Over the course of a structure's life, due to various factors (e.g. climate change) the loads may change in scale or type and new actions may arise.

To bridge the uncertainty 'gap' between expected and unexpected actions, current codes have adopted provisions to help engineers produce more robust and resilient designs[4], to introduce redundancy and robustness into the design, and to establish rules to prevent or restrict structural failures.

Common approaches to this include tie-force, alternative load path and key element methods[5]. Risk-based methods and performance-based design are also gaining traction (as established in seismic design standards) and are also proposed for exceptional circumstances, e.g. Class 3 structures.

How can structural engineers influence lean and resilient design of buildings?

The concern of many engineers is that by delivering more optimal or lean structures, existing unconsidered margins of safety (e.g. excess material capacity or neglected geometric effects) may be 'optimised away'.

Good design that is both lean and resilient (and therefore sustainable) must balance this – agreeing a level of resilience and then designing precise, optimal structures that meet (but do not exceed) this level. In design utilisation terms, this difference may manifest itself as shown in **Figure 3**.

Currently, our role in resilience tends to be through identifying likely loading scenarios and designing in robustness. To maximise resilience means to extend this to consider future risks to our built environment and the consequences of our design assumptions being exceeded. Once risks are understood, we can design in mitigation measures to reduce them and contingencies to any residual risk.

Suggested design approach

In a truly resilient building, these risks (and mitigation and adaption strategies to deal with them) are considered throughout the lifecycle of the building, from conception up until demolition. Design measures will ideally both reduce the impact of future risks, but also improve the building's adaptive capacity and, if necessary, facilitate the provision of future mitigation measures.

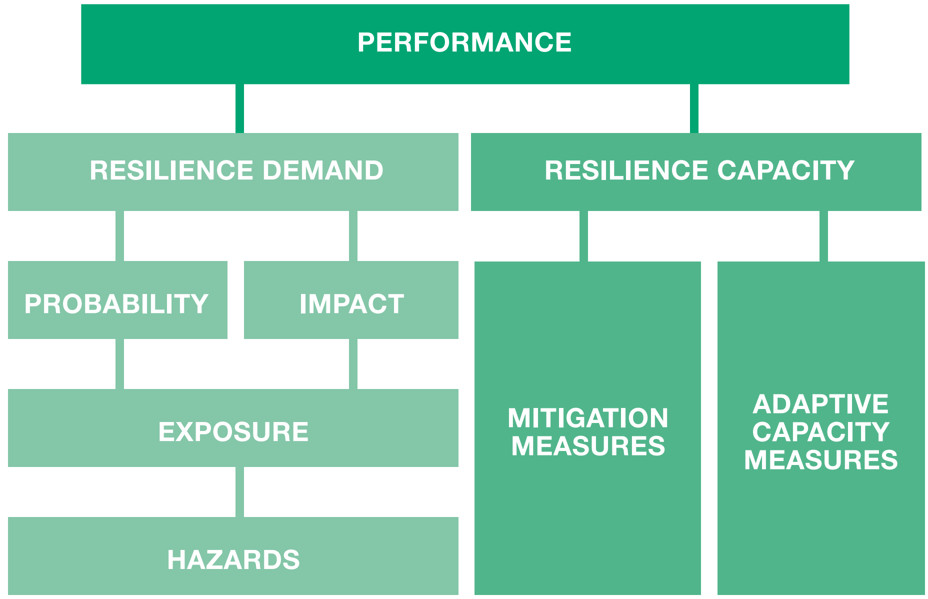


FIGURE 2: Relationship between resilience demand, resilience capacity and performance

Likewise, the building occupier is responsible for ensuring that their actions improve (or at least do not degrade) the ability of the building to respond to identified risks – and this should be communicated to our clients throughout the design process.

A key role of engineers and architects is therefore to advise the building owner of the risk, costs and benefits of their decisions.

The following steps are suggested to improve resilience while still allowing for efficient design methods to be followed.

Performance requirements

Determine what level of resilience needs to be designed into the building. This will require understanding the client's objectives and business. What value does this structure provide the client and the community? Those buildings that are critical to the community or the client's business function should be more resilient to minimise disruption. This will require an understanding of non-structural, as well as structural, building performance.

Scenario analysis

This considers potential future scenarios that may arise and how to respond. The scenarios should provide insights that are: not otherwise easily attained; plausible; distinct (not just permutations of the same theme); challenging and provide thoughtful process/insight; variable (show change over time); and relevant. This can inform the risk assessment and design parameters.

> **"THE LEVEL OF RESILIENCE REQUIRED DEPENDS ON THE BUSINESS OR COMMUNITY FUNCTION THAT THE BUILDING SERVES**

Risk assessment

This risk assessment should not simply comprise the actions that the designer expects the structure to be subjected to during its lifespan. As important are the actions that the designer has not anticipated, the 'unknown unknowns'. Factors that may affect this list include: experience in the type of structure, experience working in the geographic location, clarity of the client brief, and expected quality of construction.

Additionally, structural design codes typically focus on short-term hazards ('shocks'), such as impact, fire, floods or explosions. Longer-term hazards ('stresses'), such as climate change, poor maintenance or usage beyond design life, are often neglected.

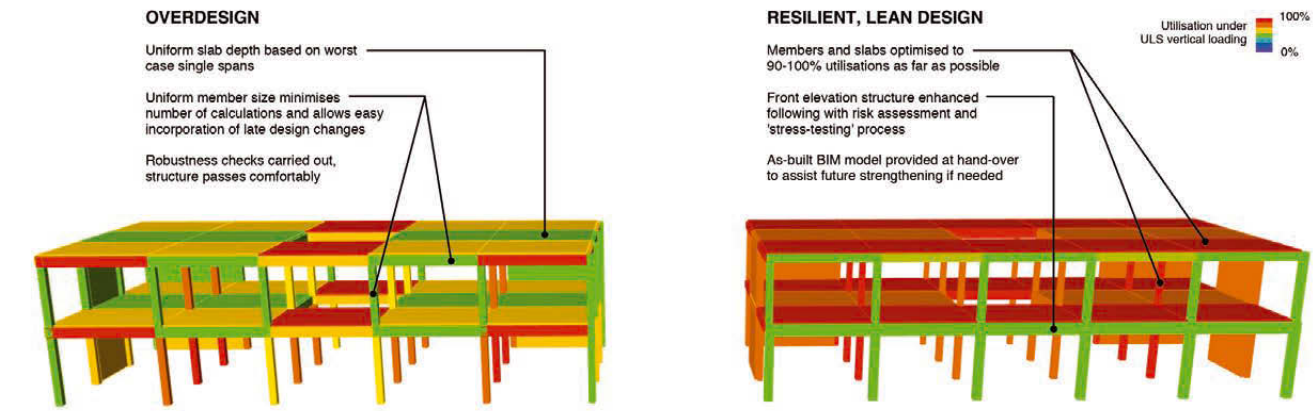
However, these factors change the basis upon which the design of the building is founded, potentially increasing the impact of other risks when they occur. For example, climate change may cause changes in groundwater levels or drying of soils. These changes in geotechnical conditions could modify the structural seismic loading profile.

It is recognised that engineers cannot think of every hazard that their structure is subjected to. Instead, we advocate that uncertainty is acknowledged and communicated in an effective manner – designers should not be afraid to state what they don't know.

Stress testing

It is proposed that building-specific 'stress test' scenarios are developed to test the assumptions used in the design of the structure and evaluate whether the degradation in performance is proportionate and tolerable (failsafe).

It is envisaged that these stress tests will have



↗**FIGURE 3:** ULS utilisations showing difference between inefficient design and resilient lean design

a number of key characteristics. They should be informed by future scenarios and ask 'What if?' questions, e.g. what if key design assumptions such as load intensity and direction, material characteristics and building lifespan are adversely modified?

The impact of these modifications on the structure should be evaluated. The degradation of the structure should also be evaluated, and its proportionality assessed. Good designs will be ones in which critical elements are stronger (such as foundations in seismic zones) and where ductile structural responses are encouraged.

Where there is greater uncertainty in the demands on a structure, or more complex load paths within the structure, it is sensible to make sure that the stress tests are more onerous. Similarly, if the building has a level of importance that would mean that failure would lead to extraordinary consequences (e.g. a nuclear power station) then it makes sense to 'beef up' the testing scenarios (e.g. longer return periods for extreme events: one-in-500-year flood versus one-in-50-year flood).

Financial and other non-structural implications should be considered. For example, while it might be structurally acceptable to close a degraded bridge for repair work (collapse has been avoided), the economic and social implications would be significant if the bridge is heavily used by commuters.

Non-linear finite-element techniques should be utilised to understand the performance and potential failure of our designs (as commonly used in seismic and blast engineering). This would identify the potential consequences of exceeding design assumptions (failsafe) and allow us to understand how close to failure a structure is. Non-structural performance should also be evaluated.

Design for adaptability

A resilient building is adaptable to future change. The asset therefore will retain its value for the owner. This can be achieved by:

- making it easy to upgrade systems when new technologies emerge
- designing in flexibility of use
- understanding the carbon that goes into our designs and seeking to minimise it while achieving other objectives
- considering climate change adaptation – designing for a changing planet, increased temperatures, droughts, floods, etc.

Collaboration

Structural engineers should work with not only the design team, but building owner and operators – particularly those in charge of business continuity and resilience – so that they understand what the building is being designed for and how that may affect their planning and response.

Repair and maintenance

We should make it easy to repair and maintain the building by selecting local, abundant materials that do not require specialist tradespeople.

Real-time monitoring

Situational awareness is a key part of resilience. Gathering the right information to facilitate understanding and appropriate mitigation or adaptive action. Utilising sensors to monitor structures and feed back to computational models will gain increasing prominence and should be included.

Conclusions

The design process is always one of compromise between competing requirements which need to be prioritised through discussion with the client. It is the engineer's responsibility to balance these and present clear risk–cost–benefit options to the client that consider whole-life costing.

Lean design focuses on maximising value; resilience focuses on protecting and enhancing value. There is a synergy here if the design is focused on delivering value to the client. This requires acknowledging and quantifying how this value could be disrupted or improved where there are uncertainties in the assumptions, and through considering future risks, change factors and opportunities.

Engineers should embrace this opportunity to design structures that are more efficient, robust and resilient in the face of a changing planet.

This article outlines some of the key aspects that should be included in updated design guidance documents to ensure that this opportunity is used to design a built environment that is truly resilient.

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