Iconic Global Structures: what can we learn?

Dubai, UAE | 29-30 September 2019

The Institution of StructuralEngineers

SEI ASCE STRUCTURAL ENGINEERING INSTITUTE

Introduction

Improving performance is a constant demand of the modern age. Doing things differently and challenging the status quo is as relevant to structural engineering as it is to any other discipline. Pushing the boundaries of what is possible and what is expected of modern built environment professionals is a serious business; and for structural engineers this means never compromising their ultimate responsibility for structural safety.

All the more reason why increasingly we must look beyond our own geographical boundaries to learn and share experiences as we seek those moments of both incremental and disruptive change that will continually enable us to transform what we do and how we do it.

Recognising the importance and power of global interoperability was the catalyst for IStructE and SEI seeking ways in which they might collectively support the profession - and to do so by utilising the expertise of their international communities and networks.

The 2019 joint conference "Iconic Global Structures – what can we learn?" is the first manifestation of our commitment to support the structural engineering profession in wrestling with the challenges of our time and to help underpin improved and innovative local delivery that draws on the strengths of global learning.

Location:

The inaugural conference took place in Dubai, a significant international hub where north meets south and east meets west. The rapid growth and urbanisation in Dubai over the last 40 years is remarkable and there remains a continuing vision for growth and development. Achieving this rate of progress from a small local population was dependent on a mass influx of built environment professionals and construction workers with a range of qualifications and experience from many countries. Codes and standards for materials, design and construction were adopted from many different sources and vary widely from city to city (as well as within cities) depending on the developer and approval authority.

Objective:

The value of lessons learned was central to the conference theme. Nine iconic international projects were discussed, categorised into three types of structure: large volume occupancy, unusual structures and performance-based design of tall buildings. Following keynote speeches, in depth panel discussions where structural engineers were joined by other experts within the broader construction industry (architects, building authorities, developers and suppliers), provided insightful reflection on changes that could improve safety, efficiency and communication.

Shanghai Tower

Technical Session Overview

1. Large volume public occupancy

These structures have special considerations in structure type and the assurance of life safety, particularly in the areas of structural reliability, security, fire protection and egress. The first session explored three structures of large occupancy that share such design and construction challenges:

1. Museum of the Future, Dubai, UAE (currently under construction)
2. Singapore Sports Hub, Singapore (winner IStructE Award for Structural Engineering Excellence 2015)
3. Tottenham Hotspur Stadium, London, UK (winner IStructE Supreme Award for Structural Engineering 2019)

Each project had very different usage requirements and site conditions, and the project teams devised unique, innovative solutions to challenges. However, some common features included:

- Close collaboration of different teams across disciplines from the outset. Co-location was most effective in sustaining a synergistic design environment;
- Early stakeholder and contractor engagement improved the design and procurement processes. The use of appropriate materials and methods for the region were key to each project's success;
- Management of workflows using technology and automation was invaluable;
- Constructability and staged analysis were an intrinsic part of design considerations. A structure can be analytically correct but may not be constructible.

Museum of the Future – key facts:

- Exhibition space of 12,000m^2 depicting the future technologies within seven, 9m high floors within a unique shell structure. The building is in front of Emirates Towers and on the main arterial road in the centre of Dubai;
- Elevated podium structure accommodating the parking, MEP areas, auditorium and F&B to raise the building above the nearby metro for increased visibility;
- Calligraphy wrapped onto the façade consists of three quotes from His Highness Sheikh Mohamed bin Rashid Al Maktoum;
- Over 1,000 bespoke GRFP panels (each 9-16m in length) and 3m wide;
- Parametric modelling adopted to develop the building's complex shape to optimise the structure;
- Early contractor engagement led to quantity optimization of steel nodes to reduce tonnage and improve constructability.

Singapore Sports Hub – key facts:

- New 55,000 seat national stadium to replace existing open stadium;
- Retractable roof to allow direct sunlight onto pitch;
- World's longest free-spanning dome structure (305m);
- Multi-purpose stadium for football, cricket, athletics and National Day Celebrations – achieved through movable tiered seating;
- Innovative mid-roof anchor point hosts winch system allowing a fully contained retractable roof;
- Cooling is distributed underneath the seats;
- Roof steel tonnage was optimized significantly through several wind tunnel testing iterations. Buckling and fatigue analysis became a principal design consideration.

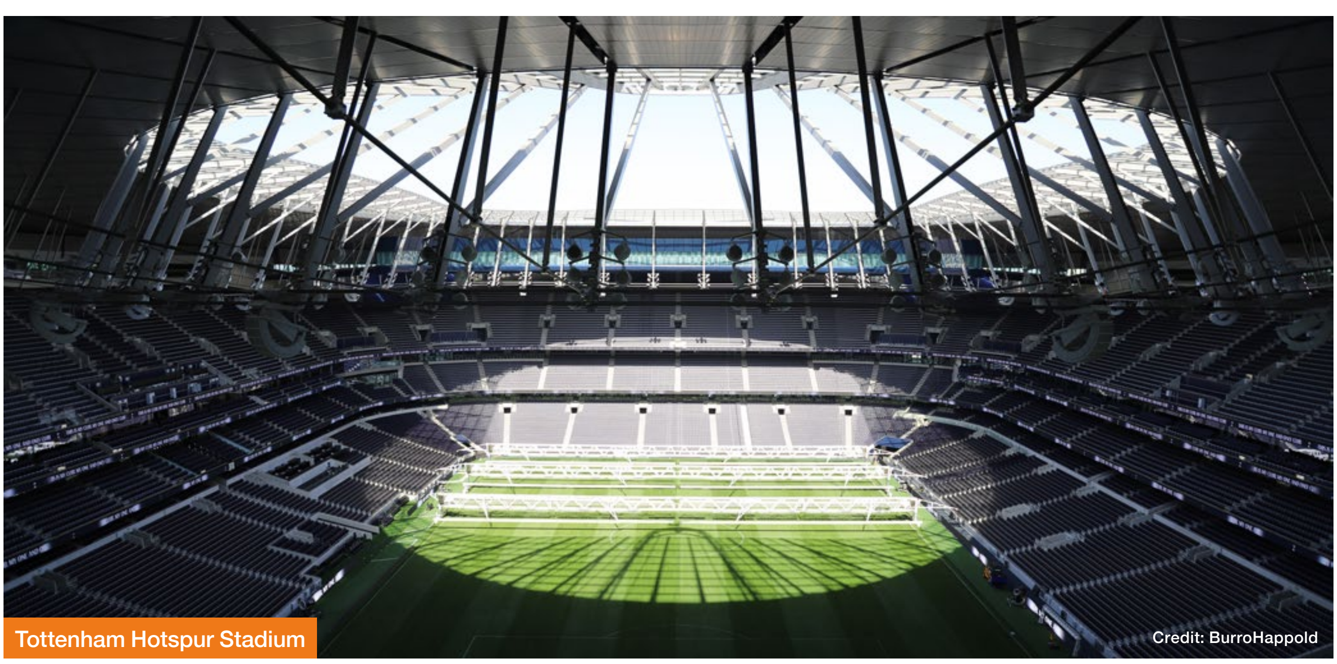
Tottenham Hotspur Stadium – key facts:

- Original stadium was built in 1899 and was difficult to access;
- New 62,300 seat stadium constructed over four years with phased decommission of old stadium to provide a new destination for the public to enjoy before, during and after matches;
- World's first 3-way dividing, retractable football pitch with synthetic turf underneath for National Football League matches, concerts and other events;
- Gravel excavated during construction was sustainably re-used for concrete floors at the lower levels;
- Extensive use of post-tensioned slabs required 40% fewer columns;
- The cable-net roof structure is key for unobstructed views. Final design was a lightweight looped cable structure with an outer compression ring and two inner tension rings.

Museum of the Future

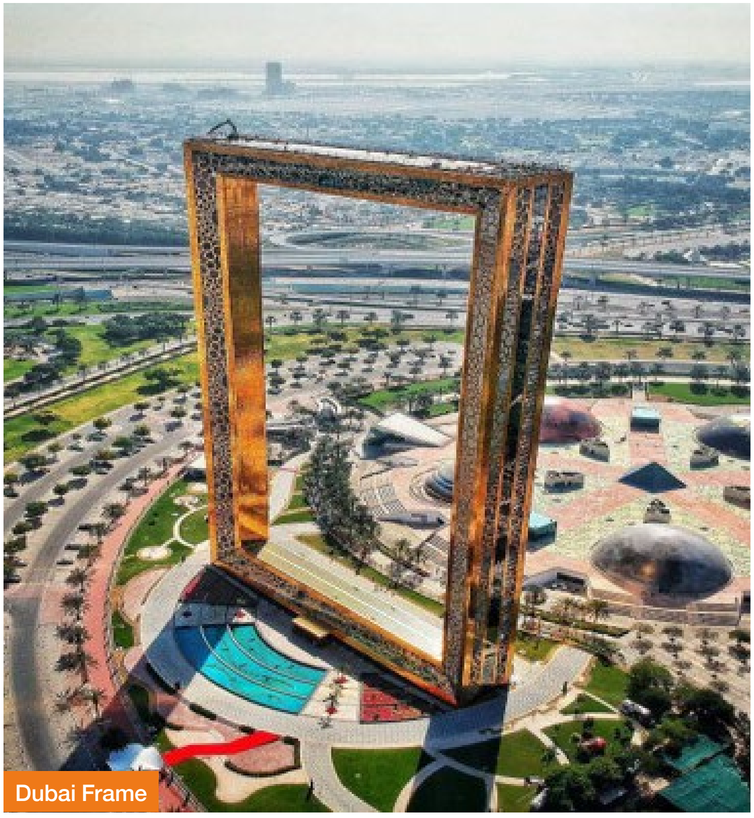
Singapore Sports Hub

Credit: Darren Soh for Arup

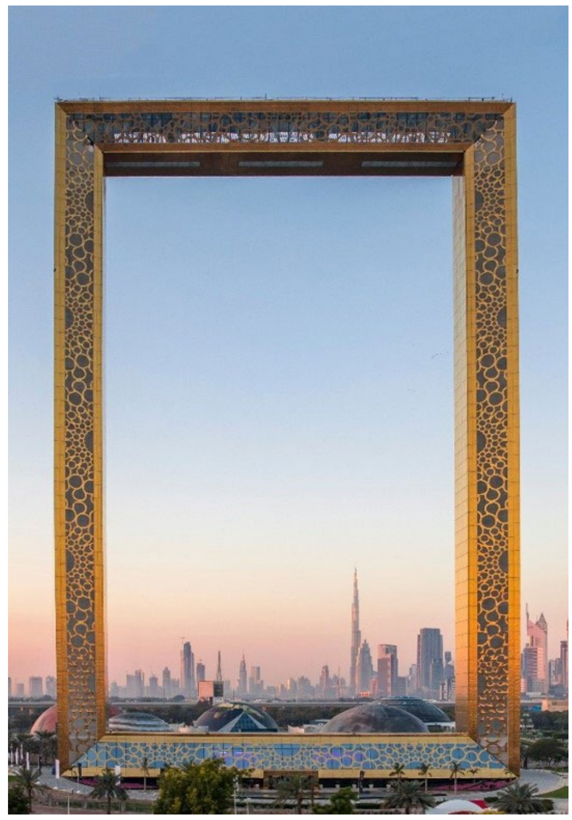


Tottenham Hotspur Stadium

Credit: BurroHappold



Dubai Frame



London Eye

Vegas High Roller

2. Unusual structures – codes do not apply

Some structures are very flexible and their non-linear behaviour falls outside the standard provisions of design codes. Three such structures were presented:

1. Dubai Frame, Dubai, UAE (winner IStructE Award for Tall and Slender Structures 2018)
2. London Eye, London, UK (Europe's tallest cantilevered observation wheel)
3. Vegas High Roller, Las Vegas, USA (world's tallest Ferris wheel)

Unusual structures require structural engineers to approach the problem from first principles instead of rigorously following codes, because design codes have limitations to their application. Designers should always consider the following:

- Recently built similar structures of a new type offer lessons in the evolution of form. The original Ferris Wheel was built in 1893 and subsequent iterations, such as the London Eye and Vegas High Roller, are prime examples of how the structural form developed across projects;
- The live to dead load ratio may vary more widely than for conventional buildings, falling outside applicable code bases; therefore, a suitable factor of safety should be considered;
- Single points of structural failure should be avoided whenever possible, through provision of alternate load paths. Robust designs should be maintained for safety.
- Codes can be used as a reference but it is important to focus on their intended use in application to unusual structures;
- Some structures may require high levels of damping to control oscillation;
- Points should be designed carefully and regularly inspected for fatigue as part of a maintenance plan.

Dubai Frame – key facts:

- A monument strategically placed to continuously frame the development of the past, present and future of Dubai situated between traditional and modern Dubai;
- 150m tall and 93m wide with clear bridge span of 75m based on the golden ratio;
- Skydeck has a pressure sensitive see-through glass floor;
- Building façade inspired by the Expo 2020 logo with titanium coated stainless steel cladding to give the appearance of shimmering gold;
- The cross-section shape was susceptible to wind-induced vibrations. Special porosity was included in the cladding design to allow air-flow and reduce drag. The legs are very flexible.
- 3% supplementary damping was provided in the legs and 5% on the bridge;
- 2,700 tonne steel bridge was assembled on the ground and strand jacked into position over two days at 3.5 mm per minute.

London Eye – key facts:

- UK's most popular paid tourist attraction;
- Original concept proposed in 1995 as a newspaper sketch competition;
- Constructed in 16 months to open on 31 December 1999;
- Height of 132 meters and capacity for 800 people in 32 pods (numbered 1 to 33 to avoid a pod numbered "unlucky" 13);
- Primary challenges:
  - Operational issues were more difficult to overcome than the construction;
  - Positioning of capsules – which needed to be on the outside rim for an unobstructed view;
  - Creating a non-gravity floor levelling system so passengers could move freely within the capsules;
  - Double curved glass for the capsules;
  - Passenger embarkation/disembarkation with the wheel continuously rotating.
- 25m spindle with a 2.1m diameter and 200mm thick steel cast in seven sections using molten steel, butt-welded and weighing 400 tonnes considered as a single cantilever supporting the structure required exceptional care in design and fabrication;
- Hub and spindle designed to fit standard bearings;
- All elements were transported to site by barge and assembled on temporary islands;
- Wheel lifted into position over two days. The first few millimetres of the lift were the most critical;
- Capsules were attached one at a time by rotating the wheel.

Vegas High Roller – key facts:

- Largest wheel in the world at 168m with a capacity for 1,120 people in 28 capsules;
- The unique spherical cabins and single-tube rim provide nearly 360 degrees of unobstructed views;
- Physical testing simulated cabin vibrations to allow key stakeholders to experience vibration criteria during the design stage;
- The rotating structure is assessed in detail for fatigue, controlling the stresses at every connection point;
- Movements and tolerances at the boarding platform were important to allow the wheel to rotate while passengers board;
- Cabin design prioritizes passenger thermal comfort given the high temperatures in Las Vegas.

3. Performance Based Design of Tall Buildings

Recent years have seen a trend for tall and super slender buildings in urban areas as congestion challenges design. These structures tend to have a long fundamental period of vibration, but their behaviour is often dominated by higher modes with non-linear effects also becoming more pronounced. Designing these types of structures using standard code procedures may not result in the desired level of safety or resilience.

Performance Based Design ("PBD") is now recognised as the future design framework of super tall and slender buildings. The goal of PBD is to limit the damage to acceptable levels by accounting for the energy that is absorbed and controlled.

Three world-class projects were reviewed in the final session of the conference to showcase state-of-the-art projects employing PBD:

1. Jeddah Tower, Jeddah, Saudi Arabia (under construction)
2. Salesforce Tower, San Francisco, USA (CTBUH winner, award for the Best Tall Building Worldwide, 2019)
3. Shanghai Tower, Shanghai, China (designed by IStructE 2018 Gold Medallist)

Jeddah Tower - key facts:

- Will be world's first 1km tall man-made structure;
- Will supersede Burj Khalifa (Dubai) as world's tallest building by at least 170m;
- Fully connected reinforced concrete bearing wall structure which continuously engages all vertical concrete elements in the resistance of lateral load;
- Rigorous regime of wind tunnel studies implemented to understand building performance in relation to structural system aerodynamic response, occupancy comfort and elevator system operation;
- The tuned shape of the tower is tapered by continuously contracting the floor plan extremities as the tower ascends, which mitigates the uniform build-up of wind vortices over the tower height reducing tower motions and controlling wind loads;
- Standard codes do not provide reliable guidance for occupancy comfort or wind response for a building of this height. Due to the structure extending above the atmospheric boundary layer, highly complex climate models were developed to predict its behaviour.

Salesforce Tower – key facts:

- Despite being 326m tall and constructed in a highly seismic area, it is designed to be one of the safest buildings on the US West Coast;
- Required the implementation of several "world-first" design methods using PBD with strict performance criteria;
- Sophisticated nonlinear seismic time-history computer modelling was employed;
- Maximum seismic demand in top two-thirds of core due to higher-mode whipping effects which could only be identified using PBD methods;
- Interaction with ground conditions and a new transit hub utilizing adjacent buildings were considered.

Shanghai Tower – key facts:

- 632m tall tower described as a vertical city;
- Optimized aerodynamic shape provides beautiful architectural lines as well as reducing typhoon force wind loads common in Shanghai by as much as 24%. By reducing wind loads, less construction materials were needed providing a greener build and saving substantial construction costs;
- Primary structural system consists of an inner core with an outer mega frame utilizing outriggers and belt trusses;
- PBD was used extensively to quantify structural performance through comprehensive testing of complete structural components and scaled structural models;
- Rigorous numeric modeling was undertaken on composite mega columns and shear walls to better understand the influence of high-strength materials and scaling-effects;
- Seismic shaking table tests were conducted on 1:50 and 1:40 scale building models to evaluate overall performance for seismic controlled design.

Jeddah Tower


Salesforce Tower


Shanghai Tower

Lessons Learned

Influence

One of the more influential sentiments heard throughout the talks concerned the extent to which the project (and thus client) would benefit from a structural engineer's expertise from day one. A structural engineer should be regarded as a trusted advisor or consultant, as well as an enabler of design. Engineers should strive to help manage expectations and avoid costly assumptions while being careful not to appear inflexible. This engineering influence brings benefit throughout the entire project. For example, one project presented a client's decision to change the structural system mid-construction based solely on non-technical opinions, leading to an unnecessarily lengthy construction time.

Collaboration

Everyone agrees that collaborative multi-disciplinary work is essential for successful projects. However, several barriers still exist such as separation between collaborators and ineffective communication. These issues are magnified on international projects. One recurring lesson was the value of co-location of collaborative teams throughout the project.

Working in the same physical space enables shared thinking and fosters new levels of expertise; ultimately leading to improved, innovative solutions.

A second barrier is less-than-effective communication. As in all professions, communication is key, but it takes concerted effort to succeed. For example, learning the language of other disciplines is time consuming, but invaluable for engineers who became 'translators' for the client and their projects' many trades. The Ferris wheel projects offered good examples of this when involving unusual trades such as capsule builders. The ability to communicate effectively within and between all disciplines leads to improved design and buildability.

Reflection

Reflection is universally agreed to be worthwhile. Yet barriers often prevent its implementation. We cannot learn lessons as a community without widespread and open reflection. Unfortunately, it is difficult for engineers (especially younger professionals) to make time for reflection at the end of each project when there is always pressure to get on with the next assignment. Perhaps company-wide policies are needed to change this culture. Relieving time pressure on professional teams will allow greater opportunity for reflection, value-added thinking and improved high-level productivity.

Beyond producing better engineers, there is a financial incentive. The economic benefit from avoiding repeated failures will no doubt outweigh the time spent on reflection.

Constructability

Another common lesson arising from our speakers' reflections is constructability issues that could have been caught during design. Simply having a vague idea of how designs will be constructed before handing them over to the contracting teams does not work, especially for unique and iconic structures. Furthermore, understanding how the developing structure behaves during construction is just as important as its behaviour when fully completed. In this respect, structural engineers can better plan for variability and consider mitigating scenarios. One example we heard was in the often overlooked interfaces designs – where problems are most likely to occur. Having someone on the team dedicated to look specifically at the interface will not only catch potential design issues, but also lead to better constructability.

Design review

Although, if poorly planned, the peer review process can impede a project's progress, it is one of our community's best practices and should be valued as such. Key is to have peer reviewers engaged with the overall team and avoid a divisive environment that could negatively affect a project's schedule and cost. One approach discussed was identifying specific objectives for peer reviewers as opposed to a more general review. This idea, coined 'objective-based peer review', would help both the reviewer and designer. It is equally important for designers to be aware of the spirit or intent of the building codes and look beyond blind code conformity. In this way, a structural engineer must channel their inner Socrates and always ask 'Why?'.

Sustainability

As enamoured with our structures as we all understandably become, it is important to step back and see our projects in the wider context of landscape, infrastructure, environment and wellness. We, as structural engineers, often are not facile with building sustainable buildings. In some of the tall buildings examples, the building alone was not the sole focal point but an anchor for the larger area around it. When rooted in long-term planning, designed and constructed with larger and longer use in mind, a more sustainable project emerges. Some of the more specific areas with room for improvement included waste management and an ability to present different design options specifically in relation to their impact on sustainability.

Salesforce Tower

Looking to the future, broadening our horizon – recommendations for more effective practice

Embrace a more expansive vision for the structural engineer's role

In an industry of increasing specialization and fragmentation we must embrace a more expansive vision for our roles. Our work is not about the structure, per se, but the role of the structure in service to our clients and society. As prime collaborators not just enablers, we must anticipate the needs of our clients and embrace all disciplines necessary for success.

The UN Sustainable Development Goals elucidate the challenges and opportunities before us. Future structural engineers will embrace a diversity of backgrounds, skills and functions. Our roles will range from niche experts to leaders of societal initiatives. We must prepare ourselves and our profession.

Be globally aware and globally adept

Whether global or local in outlook, nearly every project executed today has international components. While this conference demonstrated that the international community has much in common, there are often important geographic differences that must be understood and addressed. Issues that surfaced over the two days pertained to matters of regulation, culture, law, tolerance for risk, sensitivity to the history of the site, loads and other hazards, and labour and materials markets. We must be globally aware and globally adept.

Be a super-collaborator not a superstar

Complexity, the explosion of knowledge, the imperative for integrative delivery processes, and the speed at which modern society moves will require successful future projects to be borne from great collaborative teams rather than individual superstars.

We have much to learn about the qualities of great collaborators and in establishing effective collaborative teams and workflows. New formats such as colocation or disciplines such as the Project Interpreter (i.e. one who can help translate the language of many disciplines) are emerging. Hierarchical organizations are giving way to more complex networked relationships.

Exploit your uniquely human capacity to create and innovate

Advances in technology increasingly liberate us from drudge work, leveraging our ability to create and innovate. The successful engineer of the future will bring new competencies to the table and routinely engage in out-of-the-box thinking.

Creative work requires integration across the entire project spectrum and across all design disciplines, as well as direct consideration of product and material innovation, constructability, and structural behaviour during construction. Innovative processes require "systems thinking" to assess risks and vulnerabilities.

Dare to challenge building codes

Building codes set forth minimum requirements for design. They cannot anticipate all hazards, performance criteria, or aspects of structural behaviour necessary for every structure.

We must not blindly follow codes but rather understand their rationale and step outside their bounds when required. Often PBD results in more creative, better-performing structures.

Be good custodians

We must embrace sustainability and contribute to the challenges raised through objective resilience design. Consideration of interdependent components of resilience, robustness, resourcefulness, recovery and redundancy is essential in successful planning and design.

Learn from others and share with others

Societies and industries advance by shared learning. Whether on a project basis through peer reviews, design critiques, post-completion reflections, or through large-scale sharing via databases such as the Confidential Reporting on Structural Safety system (www.structural-safety.org) or international conferences such as Iconic Global Structures, we have much to learn from each other.

London Eye

Credit: Adrian Smith + Gordon Gill Architecture/Jeddah Economic Company

Jeddah Tower

Conclusions – Ideas for future collaboration

Although IStructE and SEI have collaborated in the past, this event was a major achievement. The conference was an example of the **power of collaboration**, bringing together talent from the two organizations and their members and demonstrating the significance of knowledge sharing. We demonstrated the **creativity** required to design and construct iconic projects — and that creativity does not stop at the borders of an office or region. Through the use of technology, our practice has become borderless and we can collaborate with other experts around the world seamlessly, giving rise to the notion of **global interoperability**. Our presenters showed examples of how the design of iconic projects are best served by not merely following the prescribed minimal code requirements, but through the use of **performance-based design** to meet the challenging environment a structure can face during its lifespan. Most notably, as custodians of Planet Earth, we need to be stewards of **sustainability** and incorporate **resilience** in every step of a project from concept to execution. Each of these themes were covered through examples presented, and could be the focused topics of a future conference.

IStructE and SEI are focused on the advancement of structural engineering practice and knowledge; however, as evidenced by the positive feedback we received, the inclusion of other disciplines in the discussions added a higher level of relevance to our mission. As structural engineers, we need to continue to be the best in what we do technically but not stop there. We can increase the significance of our contribution to the success of a project by being knowledgeable of the concerns and challenges of other professionals.

As projects become more complex and unusual, the approach to deliver them has remained focused on creativity. In the distant past, a master builder would be charged to create a structure that was significant and made a powerful statement but took years of planning and ample creativity to envision and construct, sometimes taking several generations to complete. The iconic projects of today, as showcased during our discussions, follow similar demands — with two exceptions:

Firstly, time is of essence. We demonstrated that realizing iconic projects would not be possible without creativity and collaboration, while taking advantage of technology not only to address time pressures on delivery, but to effectively engage experts from around the globe to achieve the desired results.

Secondly, the expertise is dispersed, which brings more importance to the notion of interdisciplinary collaboration and, in the case of iconic projects, super collaboration. To that end, IStructE and SEI should effectively seek other sister organizations such as AIA, RIBA, AGC, UKGC and IABSE, amongst others, to explore effective and more robust interdisciplinary collaboration.

Acknowledgements and thanks to:

Speakers and panelists:

Rob Amphlett, UK Sports Sector Leader, BuroHappold Engineering
Ian Burns, Regional Technical Director Arcadis Consulting Middle East Ltd.
Francis Charamel, Project Director, Vice-President of the Board, POMA
Jiliang Chen, Deputy Chief Architect, Tongji Architectural Design (Group) Co., Ltd.
Jiemin Ding, Chief Engineer, Tongji Architectural Design (Group) Co., Ltd.
Edward Dionne, Principal, Pelli Clarke Pelli Architects
Mary Ferguson, Senior Structural Engineer, Arup
Chris Keenan, Construction Adviser, Tottenham Hotspur Stadium
Shaun Killa, Design Partner, Killa Design
Ron Klemencic, Chairman and CEO, Magnusson Klemencic Associates
Robert Latham, Built Environment Unit Leader – Middle East, Aurecon Group
Amith Padiath, Senior Architect, Arcadis Consulting Middle East Ltd.
John Peronto, Senior Principal, Thornton Tomasetti
John Roberts, Executive Director of Operations Jacobs UK Ltd
Hendrik Stephan, Principal Structural Engineer, Aurecon
Peter Weismantle, Director of Supertall Building Technology, AS+GG
William Whitby, Associate Director, Arup
Christopher Wodzicki, Engineering Services Director, BuroHappold Engineering

Technical Committee & moderators:

Glenn Bell (Chairman) – President Elect, SEI and Board/Council Member, IStructE
Dr Hamid Adib, SEI – Vice President, Jacobs
Laura Champion – Director, SEI
Dr Shapour Mehrkar-Asl, IStructE – Director, Kling Consult GmbH
Martin Powell – Chief Executive, IStructE
John Price – Regional Chairman UAE, IStructE
Dr Derek Skolnik, SEI – Senior Project Manager, Kinemetrics Inc
Sama Srinivas, IStructE – Senior Manager, Structural Design, Engineering Office

Organising Committee:

Vanessa Green, EA, IStructE
Debbie Smith, Senior Manager, SEI
Louise Tingley, Events Manager, IStructE

About IStructE

The Institution is the world's largest international membership organisation dedicated to structural engineering. We have over 30,000 members spanning more than 100 countries and a history dating back to 1908. The primary purpose of IStructE is to lead and support the development of structural engineering worldwide, to secure a safe and resilient built environment for all.

www.istructe.org

About SEI

SEI is a vibrant community of more than 30,000 structural engineers within the American Society of Civil Engineers (ASCE) and was established in 1996. SEI drives the practical application of cutting-edge research by improving coordination and understanding between academia and practicing engineers. It also advances its members' careers, stimulates technological advancement and improves professional practice.

www.asce.org/SEI

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