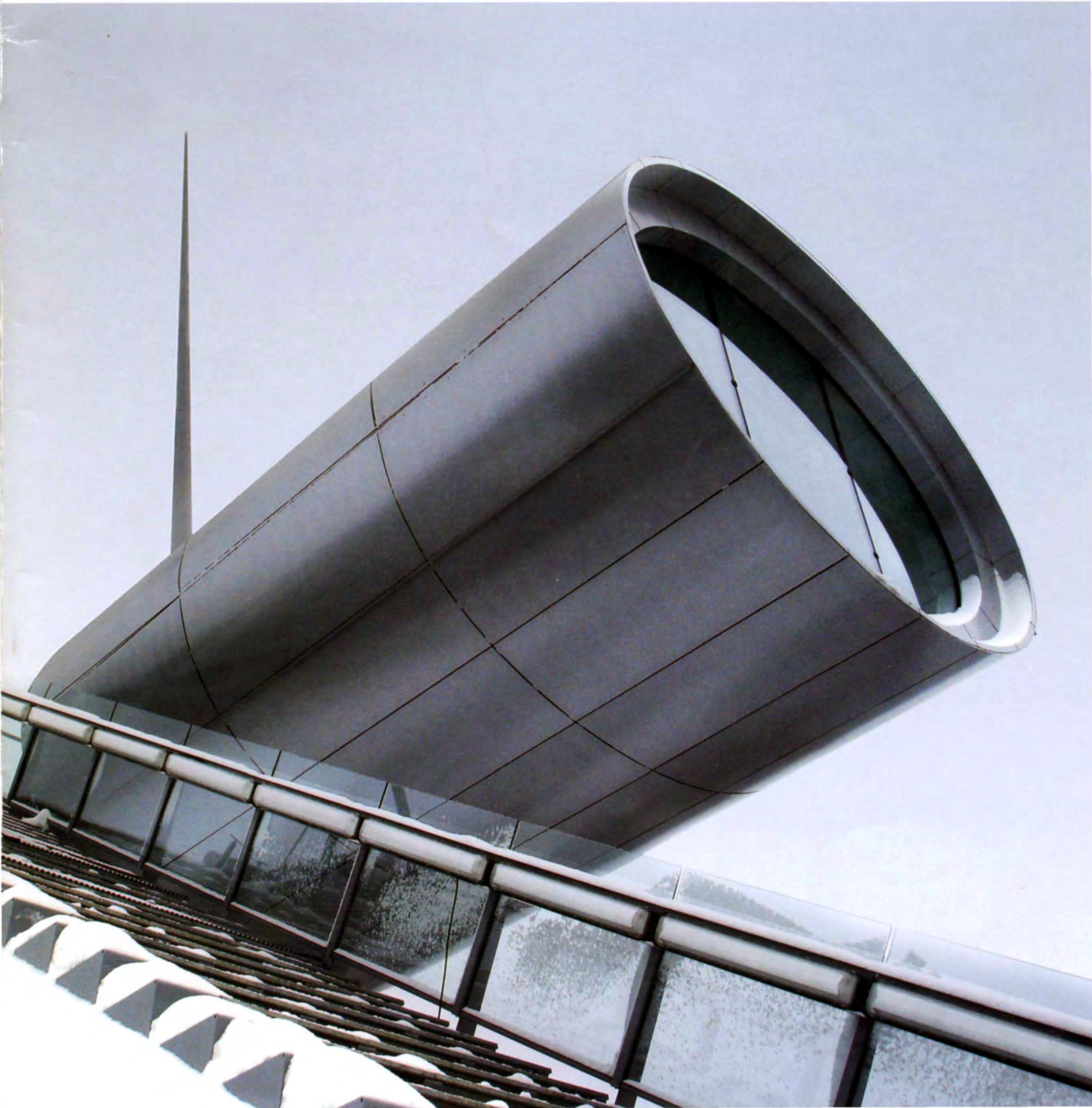
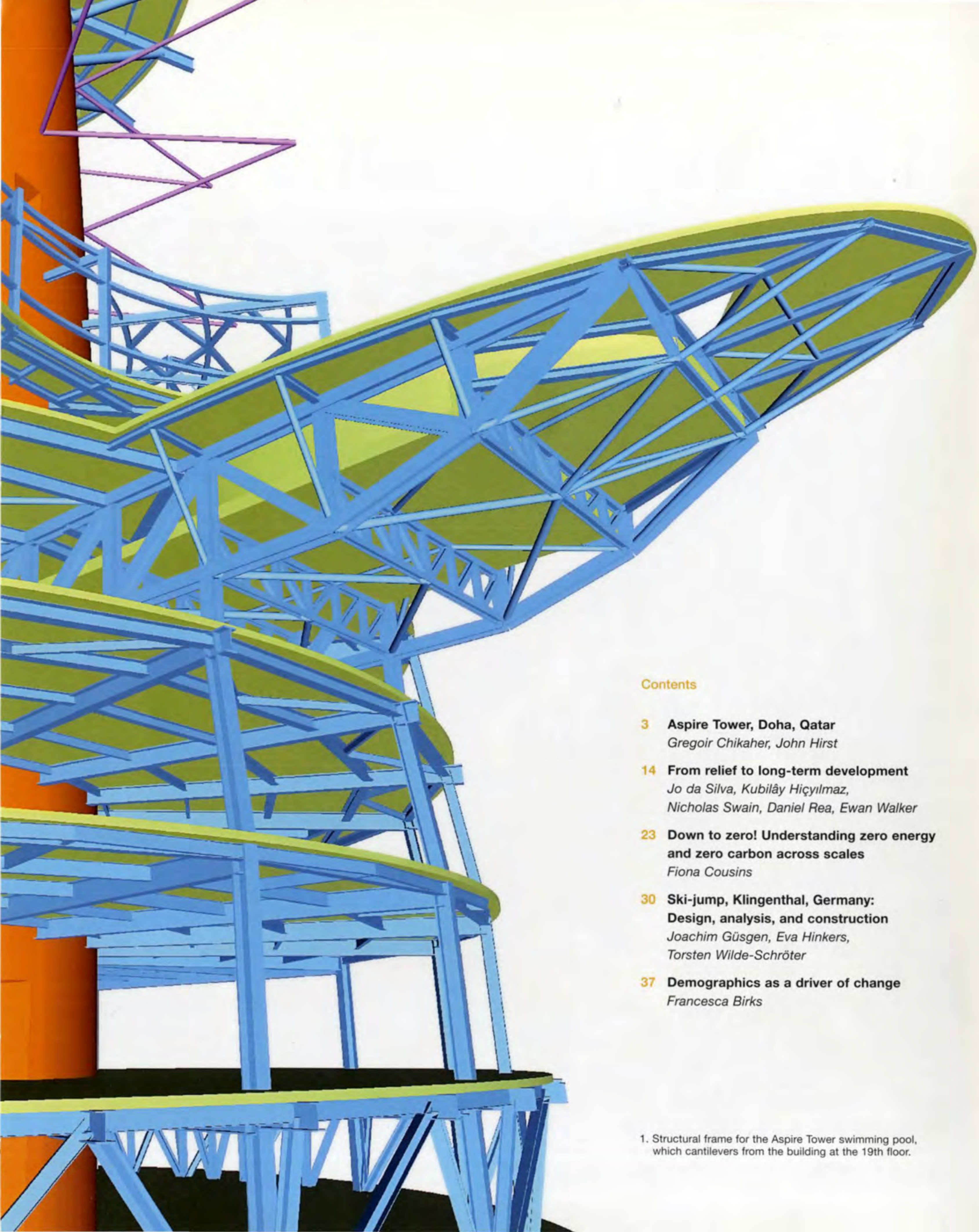
2/2007

# The Arup Journal





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1. Structural frame for the Aspire Tower swimming pool, which cantilevers from the building at the 19th floor.

# Aspire Tower, Doha, Qatar

Gregoir Chikaher
John Hirst

**At 300m, Aspire Tower is currently the tallest building in Qatar, its design symbolizing a hand grasping the torch for the December 2006 Asian Games.**

2. The completed Aspire Tower, prior to the Asian Games. Part of the Khalifa Stadium can be seen on the left.

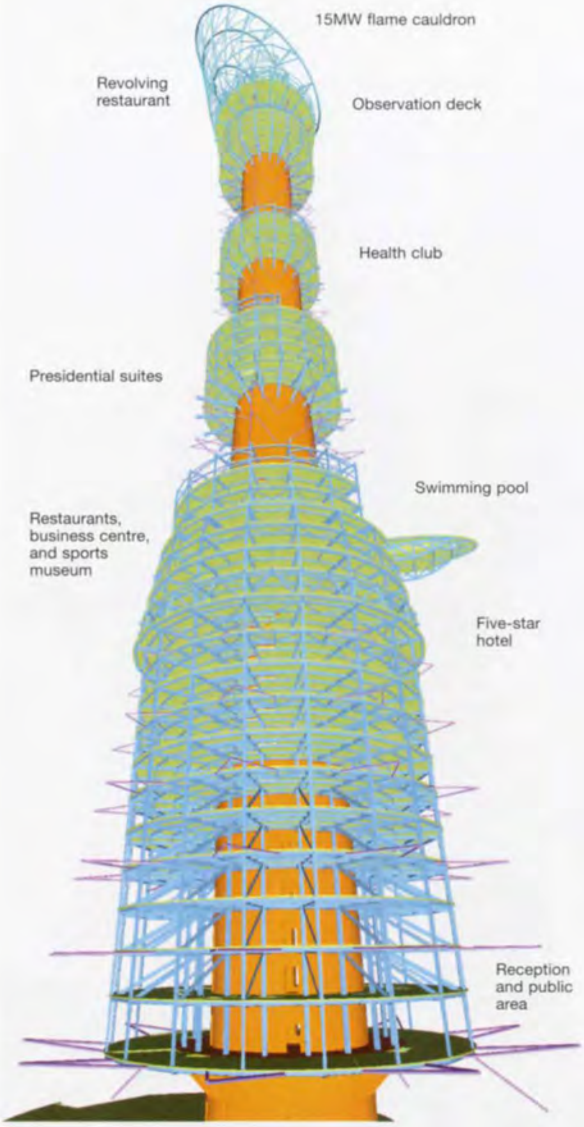
### Introduction

The 15th Asian Games, at the Sports City athletic complex, Doha, Qatar, on 1-15 December 2006, was the largest yet in the event's 55-year history. Its centrepiece structure was the Aspire Tower, shaped to represent a colossal torch, which for the duration of the Games held its symbolic flame within the lattice shell that forms the topmost section.

Arup became design team leader for Aspire Tower (at the time named Sports City Tower) in January 2005, on the basis that it would be designed and built in 21 months for the Games. Although the original joint venture partnership was replaced in April 2005, excavation for foundations had already started the previous month. Piling began in May, and the raft foundation works by August. This posed a considerable challenge to the Arup team, as it meant that the design of the substructure, superstructure, and building services had to proceed in parallel.

As had been the case with the nearby Khalifa Stadium, also engineered by Arup[1], the design and construction team was international. The main contractor was the same joint venture between Belgian and Qatari companies, Midmac-Six Construct, that built the stadium. The architectural concept chosen by the client was developed by the Qatarian architect Hadi Simaan, the executive architect, Arep, is based in Paris, and the interior designer, Ecart, is also French. Arup was the structural, mechanical, electrical, fire, acoustics, lift, and wind consultant, working with Belgian façade designers and contractors and both Italian and Belgian steel manufacturers. The design was developed under the watchful eye of the Sport City Projects Director and his team, whose aspiration was for this to be a unique landmark building. To make this a reality required dedicated effort and technical excellence by the whole team in close collaboration with the client.

As well as functioning as a support for the Asian Games flame, the tower includes a large reception and public area on two floors for 3000 guests; restaurants and business centre; 17 floors of five-star hotel accommodation; a sports museum on three floors; a health club on three floors with a cantilevered swimming pool 80m above ground; presidential suites; and a revolving restaurant and observation deck about 240m above ground. A 62m high lattice shell structure on top of the reinforced concrete central core frames the 15MW flame cauldron.




3. Principal elements of the tower.

4. The flame cauldron and lattice shell structure.

## Building summary

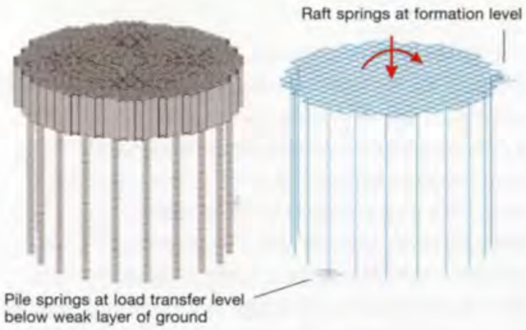
The concrete core has a minimum external diameter of 13m, a maximum diameter of 18m, and walls 1-2m thick. It reaches 238m above ground and is surmounted by a cone that supports the flame cauldron, shrouded by the lattice shell structure. The core forms the building's backbone, and supports the clusters (modules) of accommodation floors and the external envelope. Each cluster cantilevers up to 11.3m from the core independently, with no columns to the ground. The health club's cantilevered swimming pool at the 19th floor extends beyond the floor plate by over 12m.

The building envelope wraps around the core to achieve maximum efficiency, and rises as a sheer structure clad in an energy-efficient outer glass skin, with environmental systems that achieve comfort levels in the occupied spaces even when outside temperatures exceed 40°C. High-speed lifts shuttle guests to the observation deck, bar, and revolving restaurant. In addition, 140 tonnes of tuned mass damper (TMD) at the top of the tower ensure comfort to patrons enjoying Arabic hospitality in the revolving restaurant, against the dry, hot Khamsin winds.

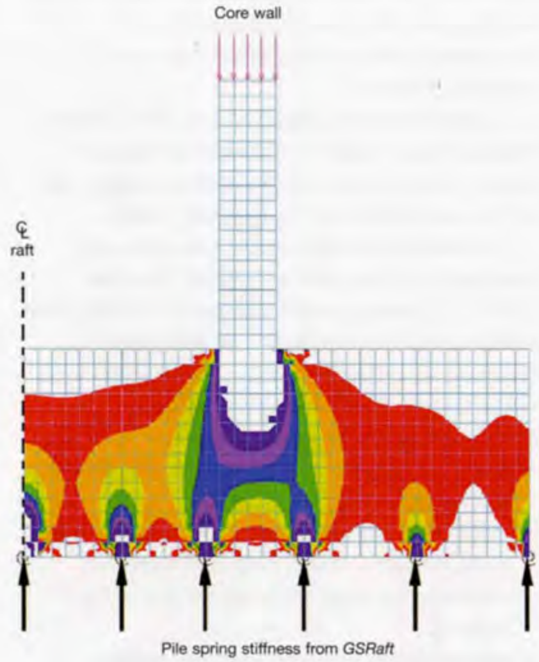
The tower is designed to carry over 71 000 tonnes of load and is supported by a 37.3m diameter raft up to 7m thick, working in conjunction with 77 straight shafted piles.

5. Aspire Tower at night, showing the cantilevered swimming pool.

6. Hotel floors under construction behind glazed façade.




7. *GSRaft* grillage model.




8. GSA axisymmetric model.

9. Pouring the 7m thick raft foundation.

### Foundations

A geotechnical desk study, which included information from the Khalifa Stadium, indicated sound limestone near to ground level, so the initial design was based on a raft foundation. While this progressed, a site investigation was made of the deeper geology and rock types - particularly important in view of the magnitude and concentration of load arising from the building form - and this confirmed the presence of weak Rus Chalk between the limestone strata, with its potential for voiding and relatively poor rock quality. In view of this and the assessment of soil/rock stress in this stratum based on the raft design already under way, the team decided that piling to the raft was needed to ensure adequate load capacity. Bored cast in situ piles were used, limited to a maximum 1.2m diameter to suit local practice, and extending through the Rus Chalk to the better quality limestone below. The piles were cast in grade C32/40 concrete for the necessary design strength.

The 37.3m raft diameter was determined by the need to spread the entire tower load delivered by the core, so as to limit bearing pressures to appropriate levels under the raft, in the Rus Chalk, and on the piles. In addition to gravity loads, the raft provides resistance to overturning effects under lateral wind and seismic loads. The arrangement provided also ensures that there is no tension in the piles or uplift, as the tension effects of overturning are balanced against the vertical load from the tower's self-weight.

The raft thickness was derived on the basis of the same loading parameters, with the central area 7m thick to deal with the total core load, and a reduced thickness of 4m towards the perimeter where load is shed into the ground.

### Piled raft analysis

A family of analysis models was used to determine the force effects for the raft structural design, with the Oasys interactive soil/structure program, *GSRaft*, being employed to analyze the foundation system.

This uses an iterative analysis system between two models, one for structure and one for soil. The structure model comprises a GSA grillage model (Fig 7) supported on springs at the underside of the raft and also at pile positions at the depth of the pile load transfer length. The soil model comprises a representation of the soil strata, with loaded areas corresponding to spring location in the structure model. At each stage of iteration soil settlements are calculated by another Oasys program, *Vdisp*, for the spring loads in the structure model. The settlements are then used to reset the spring stiffnesses in the structure model. The process is continued until vertical movements and load distributions match, providing a unique analysis for each load condition.

To assess local effects such as load spread beneath the core walls, the through thickness flexibility of the raft over an annular sector was modelled axisymmetrically, using loads and spring stiffnesses output by *GSRaft*. A lower/upper bound design approach allowed for the range of parameters involved - soil, concrete, design loads, etc.

### The core

The core's internal diameter at the base is 14m, reducing to 11m at the restaurant level. The full core terminates at the viewing gallery level, above which a concrete frame transfers lateral and vertical loads from the steel lattice shell back to the top of the core. This was analyzed for serviceability and strength under vertical and wind loading by a full dynamic method based on wind engineering data from the advisory body ESDU (originally Engineering Sciences Data Unit). The Ritz method[2] was used for the modal analysis to calculate the natural frequencies. The along-wind response of the tower was critical, as the crosswind effects due to vortex shedding are reduced by the presence of permeable mesh cladding rather than solid perimeter cladding.

A seismic analysis based on the 1997 Uniform Building Code[3], Zone 1, showed that seismic loading was not critical to the stability design, and so this was determined by the wind loading.

The vertical reinforcement in the core walls, designed in accordance with British Standard *BS8110*[4], generally varies between 0.4-0.9% of the section area. This was based on the tower's aerodynamic properties investigated through wind tunnel testing. The following effects were considered as the design progressed:

- moments induced due to local bending arising from steps in the core profile
- radial loads/moments from transfer systems to hotel, museum, health club, and restaurant
- anchoring the steel lattice for the top of the building
- restraint to the perimeter cladding system
- openings in the core and coupling beam arrangements.

The predicted peak displacement at the restaurant level from a 50-year wind was 454mm, or the height of the core from foundation level divided by 472. The predicted building accelerations from wind with return periods between one and 100 years are not within "acceptable" limits for 0.7% damping, which was assessed as the natural damping inherent within the building's structural stability system. A TMD was therefore proposed to achieve a total of some 2% damping and reduce accelerations to acceptable levels.

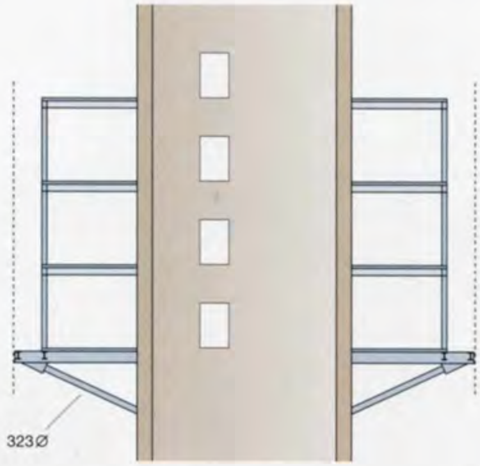
### Superstructure floors

The floors that cantilever out from the central core comprise steel beams supporting concrete slabs acting compositely with metal decking. The general arrangement has the primary beams spanning radially between steel columns and the core, with circumferential secondary beams. Steel columns in each module are supported by transfer arrangements cantilevering from the core. The presidential apartments, museum, and restaurant floors are supported off the core by steel cantilever brackets at the base of each accommodation block; these brackets also support the external cladding.

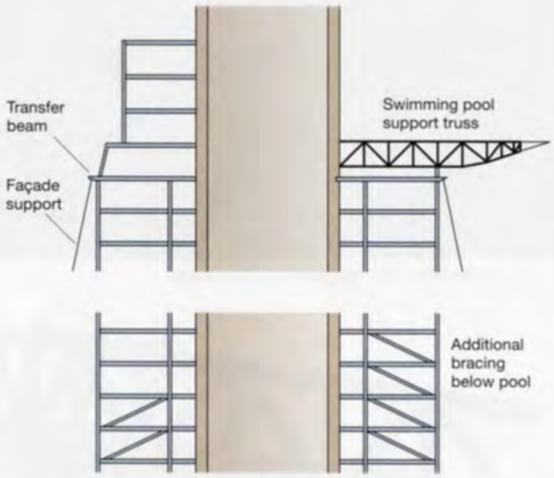
The lower viewing platform floor is similarly supported, while the upper viewing platform floor is in reinforced concrete cantilevering directly from the top of the core. The hotel, by contrast, is supported off the core by a system of vertical trusses located within the partition walls between the hotel rooms. The inner lines of the vertical trusses are in turn supported at their bases by a reinforced concrete corbel

10. Concrete core under construction, March 2006.

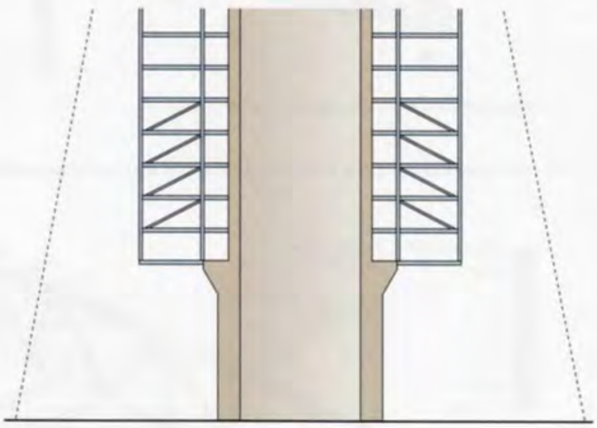
11. Upper hotel floors, August 2006.




12. Floor support bracket.




13. Upper hotel/office and health club.



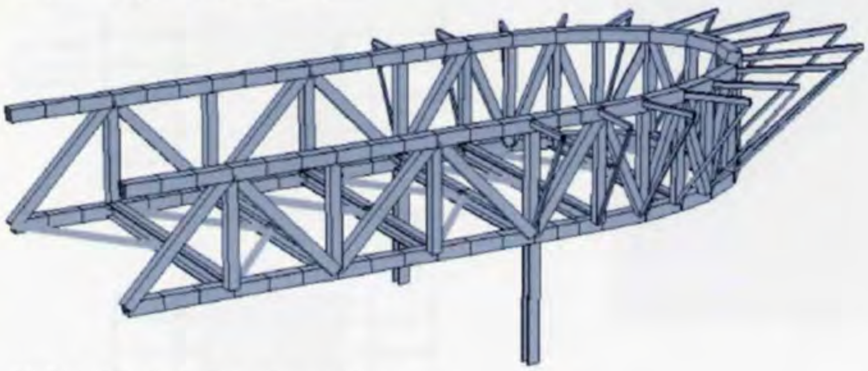
14. Hotel floor support.

ring to the core located below level 4 in the hotel lobby area. The vertical trusses are typically between levels 5 and 10. An additional level of wall bracing (between levels 10 and 11) was needed under the lift lobby and the swimming pool in order to deal with the greater loads at these locations.

The tower is entirely clad in stainless steel mesh, including the "voids" between the accommodation modules, so as to provide a unifying surface for the entire building. The mesh acts in catenary and is prestressed within individual frames that span vertically between horizontal ring trusses at approximately 8m vertical spacing. The cladding is horizontally restrained either directly by the structural floors, or by an arrangement of struts connected to the floors. In the areas between floors, the cladding is restrained by an arrangement of struts connected directly to the core.

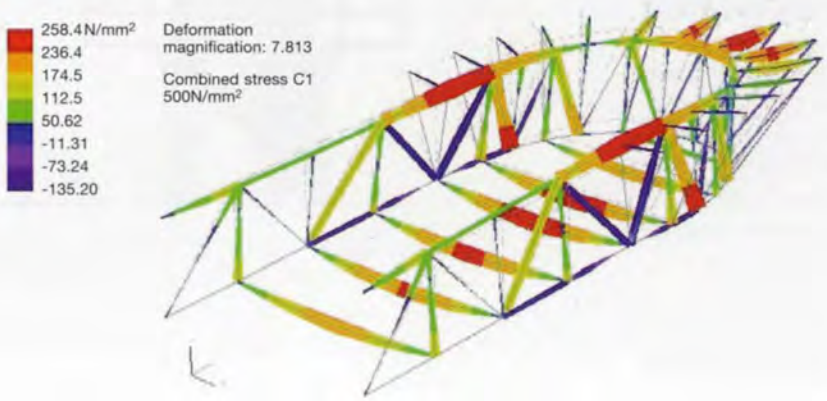
The weight of the perimeter cladding is supported by the same transfer structures that support the main floors. The cladding is both bottom supported and top hung, with horizontal movement joints provided between modules of cladding to accommodate differential vertical movement.

15. Swimming pool support truss in place.



16. Original design for the pool support truss.

17. Deflection of the steel supporting structure and the total combined stresses (ultimate values).




## Swimming pool

The swimming pool is elliptical on plan: 11m long, 6m wide, about 50m$^2$ in area, and 1.5m deep. It is a reinforced concrete box with 0.3m thick walls, supported on a substantial steel truss structure some 4m deep, to correspond to the storey height containing the pool. The plan geometry of the truss is straight from the core to the column locations, and then elliptical with approximately the same shape as the pool. The truss is connected to the core and supported on two columns that continue down through the levels below, which are supported on the vertical trusses previously described.

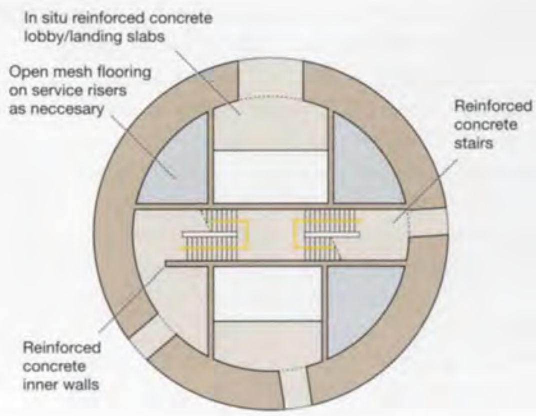
As the pool and deck area extend about 12m from the tower perimeter, the support positions for the truss are as close to the perimeter as possible to minimize the distance to be cantilevered and maximize the extension. The truss system was designed to allow the pool itself to extend 8m from the support columns with the deck area protruding a further 4m.

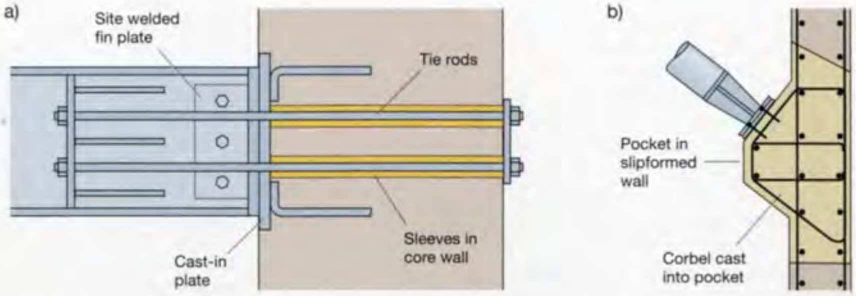
The steel structure was erected first, to provide primary support and a frame within which the concrete for the pool itself could be cast in situ. The steel structure and supports were designed to resist lateral loads and therefore required bracing to transfer loads back to the core. The pool weighs about 300 tonnes in total, of which the steel supporting structure represents just above 10% (approximately 35 tonnes).

## Internal core

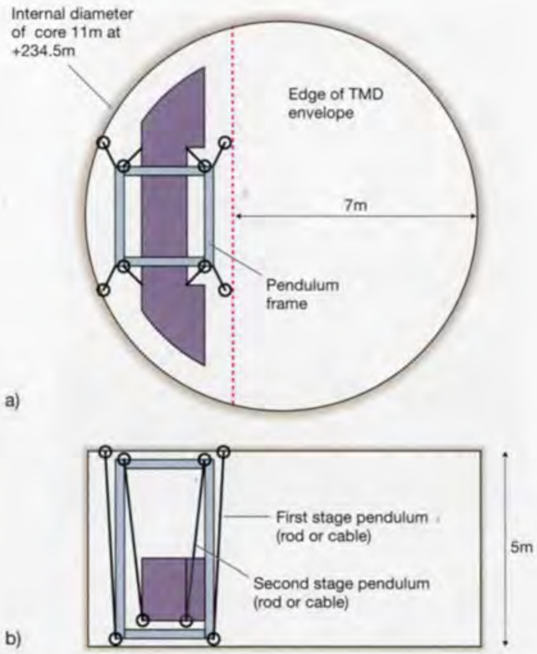
Inside the central core are access stairs, lift shafts, landings, and service risers (Fig 18). The primary internal walls are of reinforced concrete, with reinforced concrete stairs cast in situ. The design allowed for open-mesh access floors to the services risers, and additional secondary support steelwork was required to support lift guide rails, etc.

18. Internal core detail.






19. Initial concepts for a) core connection detail (with tension capacity) and b) strut support corbel detail.




20. Folded pendulum TMD.

## Connections to the core

The Arup team discussed with the contractor how the steel beams should be connected to the core, which was slipformed throughout its height, including the corbel section at low level and the frame at the viewing gallery level. Steel plates were cast into the wall at floor beam locations and anchored back into the body of the core. These embedded plates were surveyed and connections for the floor and transfer beams were welded on site.

## Damping

Assessment of the building's performance indicated that additional damping would be needed to reduce lateral accelerations at the top under wind loading and so improve comfort levels. A feasibility study of various options for a total of 2% critical damping indicated that a TMD directly below the highest viewing level was the most practical solution for the range of predicted frequencies, and so a 140 tonne (active mass) folded-pendulum TMD with a steel mass was installed within the tower core. Fine tuning to the tower's measured natural frequency was achieved by adjusting the pendulum lengths. The "fold" in the pendulum reduced the height of the required envelope by about half, but needed a rigid frame to transfer the tension between the first and second stage members. Shaping the TMD mass in this way facilitated fitting the damper within the circular plan shape of the core (Fig 20).

The detailed design, manufacture, testing and tuning of the TMD container was undertaken by a specialist contractor. Energy dissipation of the TMD is achieved by "pot dampers" which also incorporate bumper stops to prevent excess movement of the mass in extreme situations.

## Cladding support systems

As already noted, the whole tower is clad in stainless steel mesh of varying permeability, apart from the bottom few metres. The hotel lobby, up to some 63m, is fully glazed within the outer mesh surface; this glazing is subject to wind load, and has significant thermal performance requirements as the upper levels of the hotel lobby get hot. Apart from the mesh and the hotel lobby glazing, the rest of the cladding is fairly conventional. It typically spans floor-to-floor (typically 4.05m apart), either directly or with supporting mullions.

JAP, the Belgian cladding supplier, proposed supporting the lobby mesh cladding and glazing in panels typically 8.1m high (ie two hotel storey heights), with six panels for each 20° of circumference giving a total of 108 panels on plan. The even number of subdivisions gives greater planning flexibility as it allows the use of the half grid. Above the lobby, the number of mesh panels was reduced to three for each 20° segment, ie 54 in plan for the total circumference. In the hotel lobby zone the external mesh and the glass are separated by about 1m. JAP proposed to link the frames carrying the mesh and glass to form a truss supporting a maintenance walkway. To reduce the number of struts here, the truss was designed to span one ninth of the circumference. Where the large cladding panels or the lobby trusses connect to the struts, movement joints are provided to avoid thermal stresses.

21. Detail of support for façade mesh.

22. The diagrid and flame support, October 2006.

## The top of the building

**Structural elements**

The 62m high steel diagrid frame tops out at 300m above the reference external ground level. The diagrid forms the lateral stability system for this part of the building, and also supports the cladding down to the restaurant floors. The diagrid springs from a substantial concrete frame: a 1m wide and 1.5m deep circumferential ring beam supported by nine concrete columns each approximately 1m by 1.5m arranged radially on top of the concrete core wall. The top of the concrete core wall is approximately 233.3m above lobby level, the top of the frame some 4.5m above that.

The primary loadbearing elements are the circular hollow sections (CHS) that form the diagrid shell, which vary from 610mm diameter near the base to 457mm diameter at the top. The shell is restrained laterally by a series of horizontal trusses outside the "petal" at 8.1m vertical centres, spaced to coincide with the cladding system's horizontal support elements and sized to accept horizontal loads from it. The upper levels of trusses are in 500mm x 200mm rectangular hollow sections (RHS) and 300mm x 300mm square hollow sections (SHS), while the lower levels have 300mm x 300mm SHS.

The vertical loads in the outer plane of the structure, ie just inside the cladding line, are carried by 18 hangers, 120mm x 120mm SHS, equally spaced around the building perimeter. The outer booms of the trusses span between them for vertical load, whilst they restrain the truss booms against buckling out of plane. At the head of the outer plane there is an "eaves trimmer" - the rim of the "petal" - formed from 610mm diameter CHS. It carries the vertical load in the hangers, spanning between the heads of the diagrid elements and acting in biaxial bending to resolve the forces in the diagrid elements that do not node out regularly at the ring. In addition the eaves trimmer carries wind load and/or vertical load from the cladding connected directly to it.

The diagrid is a tall, relatively light structure that is subject to significant lateral loads. As a result, substantial tension forces are generated within it under some load situations. The steel structure is well able to deal with these, but this behaviour also gave rise to the potential for physical uplift and considerable movement of the base of the shell from the supporting structure. To cater for this effect, the base of the lattice shell is attached to the top of the core by clusters of vertical prestressed bars extending down into the body of the core. these clusters consist of either four or six prestressed bars, each stressed up to 3200kN, and anchoring 300mm thick baseplates of the lattice shell nodes to the supporting concrete. Installing these bars and the associated anchor plates, ducts, and anti-bursting reinforcement was a considerable challenge for the contractor.

**Structural action**

*Vertical loads*

At the diagrid rim, the hanger loads are collected by the eaves trimmer. This is curved in plan and elevation, so there is no direct line-up between the hangers and the diagrid members. The eaves trimmer must therefore carry torsion as well as bending moments in two directions, shear in two directions, and axial force. The splice connections in the eaves trimmer are bolted connections offset from the diagrid members. The diagrid CHSs then carry the loads in compression to the head of the core where they are resisted by the bearing of the connection nodes onto a grout layer on the head of the core walls.

The building's asymmetrical shape means that the cladding and self-weight loads on the high side are significantly greater than on the low side. In addition to the overall compression, this generates an overall bending moment in the diagrid shell system, carried in the same way as the moments generated by wind load in the wide direction.

*Horizontal loads applied in the wide direction*

This is the critical direction for wind loading because (a) the widest face area is exposed to the wind, and (b) the structural depth available to resist the loads is at a minimum.

The wind applies pressure to the cladding system, which spans 8.1m vertically between horizontal trusses. The horizontal trusses collect and redistribute the horizontal component of the wind load and transfer it to the petal diagrid, which resists by push/pull action in the inclined CHS members and transfers it down to the connection at the head of the core. Each level of horizontal truss contributes to the push/pull in the diagrid CHSs and so the magnitude of the forces in the diagrid increases down the structure until it reaches a maximum in the level immediately above the head of the core. The forces distribute themselves elastically through the grid structure so that there are compressions on the downwind side of the shell structure, tensions on the upwind side, and opposing pairs of compressions and tensions in between.

This is analogous to a vertical cantilevering action in an idealized beam element.

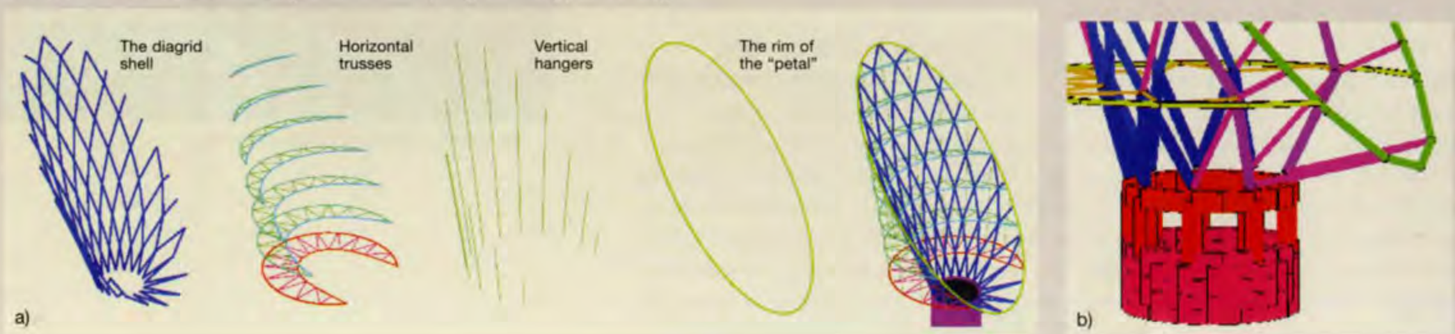
Axial shortening of the compression elements and extension of the tension elements lead to an overall downwind deflection of the top of the structure - its most significant deflection mode. Elements were sized to limit this deflection and keep its effect on the racking of the cladding panels within reasonable limits.

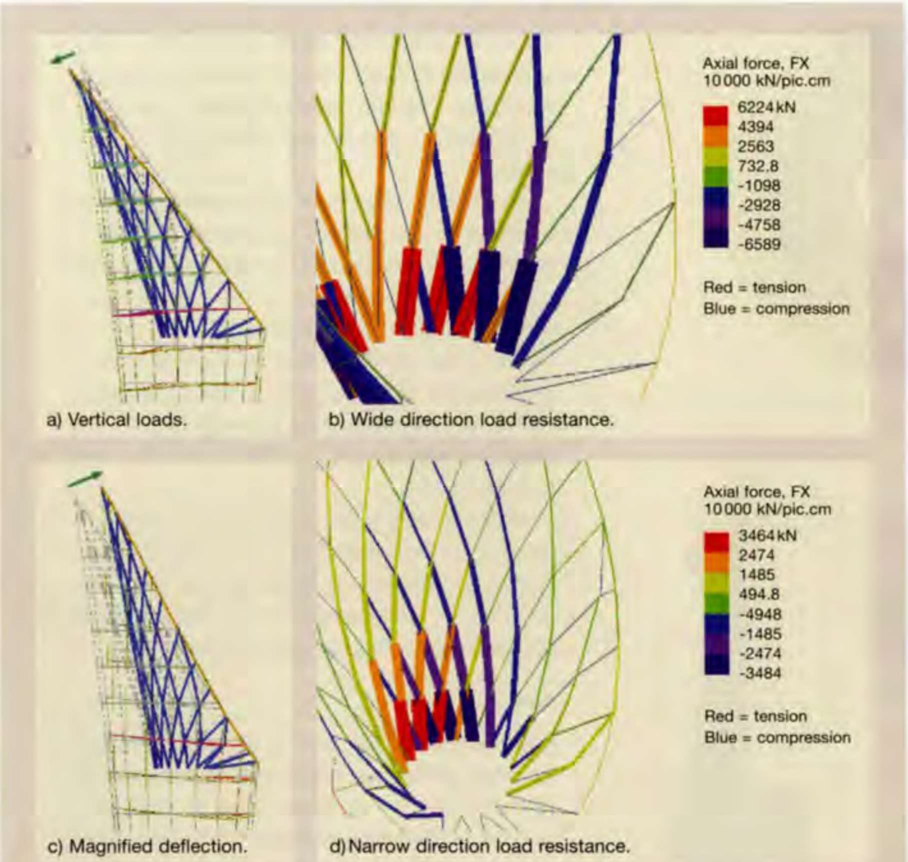
*Horizontal loads in the narrow direction*

The structure works similarly for narrow direction wind but, as the loaded profile is narrower, the overall loads on the diagrid are less. Also, the width of diagrid perpendicular to the load direction is greater, so the push/pull action resists loads more efficiently. However the eccentricity of the centre of action of the load does give rise to an overall torsion in the diagrid in addition to the overall bending. This is resisted by the diagrid just as it resists the other shear forces, by push/pull action in the diagonal CHSs.

24. The lattice diagrid, August 2006.

23. Structural elements of the diagrid frame and b) ring beam support for diagrid.






Vertical loads from the cladding are applied to the outer horizontal booms. The booms span between hangers. Hangers carry these loads to the eaves trimmer at the rim of the diagrid. Note that the hanger connections must carry the whole hanging load through the node points.

25. CAD modelling of structural loads.

### Wind loading and wind tunnel testing

Meteorological data on wind speeds enabled an analysis of extreme winds to be undertaken. This analysis indicated a gust reference design wind speed of 38m/sec to *CP3: Chapter V: Part 2*[5], which was the reference code specified by the client. This analysis was accepted as the design basis for the tower and allowed a reduction to the normal reference design wind speed in Doha.

Wind tunnel studies were undertaken at a facility run by the specialist company BMT Fluid Mechanics. These provided aerodynamic design data on which to base computation of the tower's response, as well as assessing the potential of a vortex shedding resonant response.

Overall aerodynamic coefficients were derived from wind tunnel testing, and were used to review the values adopted in the initial design stage. This permitted a more accurate assessment of overall structural loads and accelerations at the top occupied level. Forces were measured on 1:100 scale sectional models of the top of the tower and a middle section (these being most relevant to the overall behaviour of the tower). A high-frequency force balance at the base of the models was used to measure forces on the model. Modelling of the surface mesh was particularly important, and full size samples were tested together with a scale representation of the mesh so as to provide appropriate representation on the wind tunnel model. Aerodynamic coefficients were derived from the measured force values and the geometry of the tower.

### CAD

The tower superstructure was modelled in 3-D using *Tekla Structures* software. This provided valuable co-ordination and representation of complex elements, including the diagrid, where 2-D CAD would clearly have been inadequate.

### Building services design

To design and build the 300m tower in 21 months was a huge challenge. Qatar's desert climate, with temperatures as high as 50°C in summer, plus Doha's high humidity levels, make it vital that the plant and equipment perform to their design parameters without failing. The building envelope has to achieve maximum thermal efficiency and comfort levels in the occupied spaces whilst giving guests panoramic views of the city. Detailed studies were carried out, including building physics with simulation software, to select the best glazing and mesh properties to reduce overall cooling load and energy consumption.

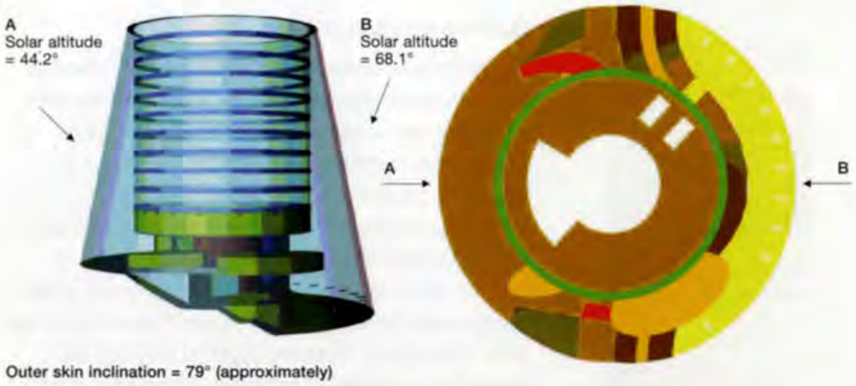
The MEP systems were designed to relevant international standards but incorporate Qatar codes and regulations. The main considerations in Arup's design of the systems included comfort, reliability, life safety, energy efficiency, space for plant, and speed of construction.

The tower's estimated electrical demand was 7MVA with a peak cooling load of 7MW; two independent 11kV power supplies are connected to the network and operate simultaneously to share the load. Each, however, can supply the full load if the other fails, to give high resilient power supply for life safety and hotel operations. 11kV switchrooms at the basement and revolving restaurant levels act as nodes for the local 11kV distribution network.

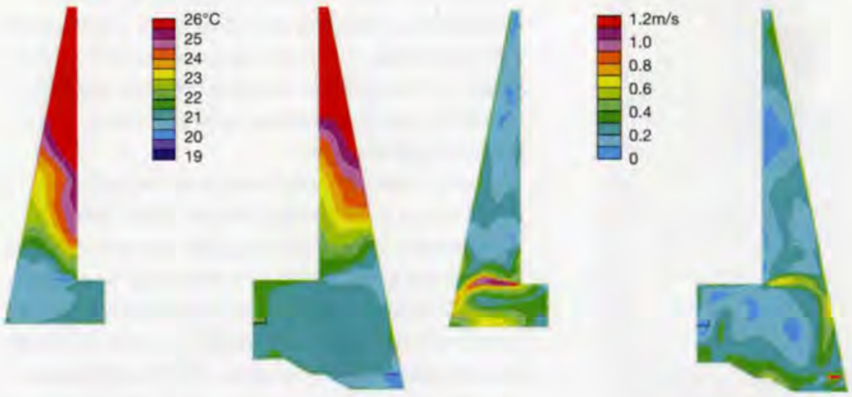
A 350mm diameter chilled water connection links to the main energy centre with flow and return temperatures of 6.5°C and 14.5°C respectively, and a chilled water flow rate of 223 litres/sec. Stand-by generators serve the life safety equipment, security systems, commercial operations, and data/communication systems.

As the tower comprises discrete blocks of accommodation connected to the central core, the extent of the MEP services running within the core was limited so as to speed its construction and maximize the accommodation space. Only the main lifts and the chilled water, electrical, and water installations were located in the core to connect the health club, museum, and restaurant levels to the plant in the basement. Each of these includes air intake and exhaust points for the air-handling units (AHUs) serving each discrete block.

The chilled water system comprises series of sealed pressurized circuits, operating on variable flow to match the anticipated high diversity factor and reduce energy demand. The building is divided into four pressure zones: the lowest serving the basement only, the second up to health club level, the third up to museum level, and the fourth the revolving restaurant and observation deck.




26. CFD modelling for air movement and temperature.




27. Environmental zones.

To reduce pressure ratings, a plate heat exchanger at health club level serves the upper floors. All terminal units and AHUs were designed with two-port control valves to maintain the required enthalpies. Because of high ambient water temperatures, the swimming pool water is also cooled by plate heat exchangers to maintain a temperature of 30°C.

To predict air movement and comfort level, especially for the ground floor lobby and restaurant areas, a computational fluid dynamics (CFD) model, STAR-CD, was used to calculate the air temperature distribution and air movement in the atrium. The light ray tracing software Radiance was used to calculate the direct and diffuse solar radiation distribution as inputs to the CFD model. This included the complex transmission, absorption, and reflection properties of the external shading elements and glass façade combination.

Arup's innovative approach to the mechanical design was to create a two-zone environment with air supply nozzles mounted around the inner core at level 4 and a series of binnacles in the lobby area. The low zone was predicted to be well mixed within the target air temperature range, whilst the high zone had stratified conditions - less critical as it was outside the occupied zones. The two-zone approach results in an effective distribution of temperatures.

Both the nozzle and binnacle supplies were optimized (throw angle, flow rate, supply temperature, location) to give an acceptable balance of air temperatures and speeds in the occupied zones, whilst the external mesh and façade glazing combined to reduce direct solar transmission to acceptable levels. The complex annular flow of high-level air between the unshaded and shaded sides of the atrium and its impact on the nozzle system was understood through this high resolution approach. In addition, comfort levels (air/radiant temperature, air speeds) in the occupied zones could be assessed.

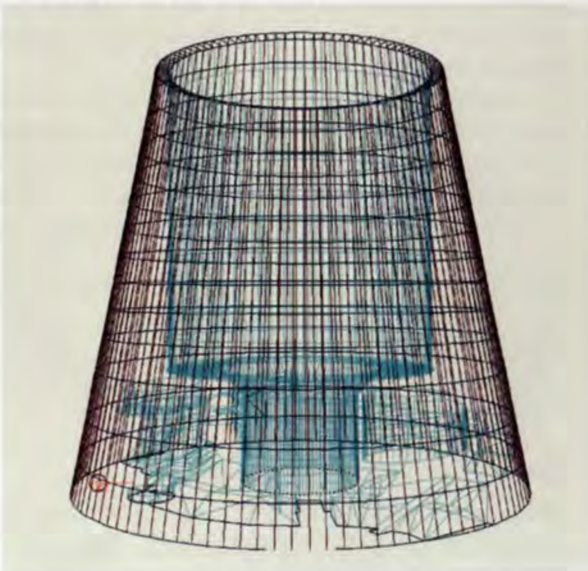
To minimize plantroom space and improve the efficiency of the mechanical systems, terminal cooling units and AHUs were selected to control cooling and dehumidification. The minimum ventilation rates were based on ASHRAE and CIBSE guide recommendations. Terminal units, especially for the triple-height ground floor lobby and restaurant areas, were selected to be integrated with the interior design, and cool only the occupied areas.

Heat recovery systems are used to recover coolth from the exhaust air to pre-cool the hot outside air entering the AHUs, all of which were designed for minimum fresh air to reduce the overall cooling load and energy consumption.

### Acoustic design

Apart from the usual aspects of acoustic design, two were particularly interesting. As the tower is clad with mesh to visually alter the profile, its height and the wind climate indicated high levels of wind-generated noise. Once the wind magnitudes and frequencies were established, the mesh profile had to be adjusted for the presidential suite area. This was confirmed by the specialist cladding suppliers who tested the mesh at different velocities and frequencies using a wind turbine. Arup used 3-D animation to develop the acoustic analysis of the large atrium area at ground level, the results of which aided the architects and interior designers with their design and choice of materials.

28. Acoustic model of the atrium.



29. The Aspire Tower and Khalifa Stadium during the Games.

## Fire engineering

A highly fire-engineered approach was necessary for the tower's fire safety design, making use of its architectural features to achieve the expected level of safety and at the same time minimize costs. In the absence of specific local codes for high-rise buildings in Doha, this fire strategy was based mainly on the approach described in various appropriate British Standards, chosen for their good guidance on tall buildings and provision for fire-fighting activities.

The fundamentals of the escape route design were largely determined by the cylindrical structural core design: two exits from each storey into opposite sides of the core, from a racetrack corridor on the hotel levels, served by two separate stairways in the core. The designed floor-to-floor height allowed the scissor stair arrangement. The very robust core wall provides a high degree of fire protection, and pressurization keeps smoke out of the escape stairways.

As the various accommodation sections are spaced up the tower, this separation between groups of floors enables staged evacuation in the event of fire, reducing disruption from unwanted fire alarms and making better use of the available stair capacity.

The automatic sprinkler installation was designed in accordance with *NFPA13*[6], for the protection of all areas, including fire hydrant system throughout the building in accordance with *NFPA14*[7], for a Class I standpipe system. Gaseous flooding systems were specified for the electrical rooms and data processing rooms. Analogue addressable, intelligent fire detection systems are networked, together with "fire survival" bi-directional communications to a master control and monitoring panel. The fire alarm system operates on a two-stage principle and is linked with a voice-alarm system consisting of alert and evacuation alarms in public areas. Emergency lighting is provided along all escape routes and egress points.

## Conclusion

All the main structural elements were completed within the 21 months specified for the tower's design and construction, enabling it to fulfil its designated function for the 2006 Asian Games. Work on the interior spaces continued after the conclusion of the Games, and were completed during the first half of 2007. The Aspire Tower has proven to be a momentous project, of which the entire concept, design, and construction team is very proud.

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**John Hirst** is a structural engineer and a Director of Arup in the Building 6 Group. He was lead structural engineer for the Aspire Tower.

**Credits**

**Client/main contractor:** Midmac-Six Construct JV **Concept architect:** Hadi Simaan **Executive architect:** Arep **SME, fire, acoustics, lift, and wind engineer:** Arup - Andrew Allsop, Chris Armstrong, Darren Barlow, Christopher Brown, Tony Campbell, Lee Carter, Valerie Chan, Gregoir Chikaher, Dave Choy, Dean Clabrough, Paul Cross, Antonio Pimentel da Fonseca, Pat Dallard, Andrea de Donno, Ian Fellingham, Ian Feltham, Anthony Ferguson, Martin Finch, Pietro Franconiero, Eiji Fujii, Neal Gardiner, Alexej Goehring, Steve Harris, Mike Hastings, Kelvin Hindson, John Hirst, Ed Hoare, Graham Humphreys, Shaed Jalal, Seb Jouan, Martin Kirk, Joanne Larmour, Charles Macdonald, Steve Macklin, Adam Martin, Martin McGrellis, Steve McKechnie, David Mills, Paul Morrison, Brendon Moss, Julian Olley, Ender Ozkan, Steven Parker, Navin Peiris, Daniel Powell, Nihal Rajapakse, Laurence Reed, Ricky Reynolds, Colin Roberts, Agnes Rothery, Nick Rushton, Ray Sciortino, Alfonso Senatore, Martin Simpson, Les Stokes, Joe Sumners, Jens Tandler, Martin Tarnowski, Richard Terry, Pete Thompson, Camilla Thomson, Gareth Thyer, James Watts, Ian Vigrass, Mick White, Michael Willford, Derek Woodcraft, Darren Woolf, Ray Young **Interior designer:** Ecart **Cladding mesh contractor:** JAP **Wind tunnel facility:** BMT Fluid Mechanics. **Illustrations:** 1, 3, 4, 7, 8, 16, 17, 23, 25-28 Arup; 2, 6 Hadi Simaan; 5, 9-11, 15, 21, 22, 24, 29 Midmax-Six Contract JV; 12-14, 18-20 Nigel Whale.

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1. Strategic strengthening of brick masonry for earthquake resistance in rural Kashmir: Arup provided technical assistance for the aid agency GOAL's programme of disaster relief following the South Asian earthquake of 8 October 2005 (see pp16-17).

# From relief to long-term development

Jo da Silva

**"Humanitarianism implies a social conscience, a wish to do socially useful work, and to join hands with others fighting for the same values"**

Ove Arup, Key Speech, 1970

A humanitarian attitude, and the desire to do socially useful work and improve lives, are at the core of Arup's values. As a result, the firm has always encouraged its staff to contribute their skills and expertise to help others, in particular non-governmental organizations (NGOs) working to relieve suffering in the aftermath of disasters, or to improve the quality of life for the poor in developing countries.

Arup has been a Patron of RedR since its formation (as the Register of Engineers for Disaster Relief) in 1982, and has supported Arup staff who are RedR members to help the humanitarian sector provide relief and assistance in many post-disaster or post-conflict situations. Among others, these have included the Gulf War (1991); the genocide in Rwanda (1994); the earthquake in Montserrat (1995); Hurricane Mitch (1998); Kosovo (1999); flooding in Mozambique (2000); Afghanistan (2003); the Pakistan earthquake (2005) and East Timor (2006).

In recent years, in recognition of the growing number and complexity of disasters and the humanitarian sector's need for technical assistance, the policy to release staff for RedR assignments has been extended to cover direct requests from other humanitarian bodies. After the Indian Ocean tsunami of December 26 2004, six Arup staff gave a total of 33 man-months' expertise in water, shelter, infrastructure, and project management to several NGOs and UN agencies in Sri Lanka, Aceh, and India. This was in addition to £200 000 donated directly through NGOs.

Relief, however, is only a short-term solution, focused on preventing loss of life and promoting early recovery, thereby seeking to minimize the longer-term socio-economic impact of disasters that can set back the development cycle several years. Yet it is development itself which is instrumental in reducing poverty and thereby improving the resilience of communities to future shocks. These may be sudden, like cyclones or earthquakes, or relate to risk that accumulates or alters over time, such as flooding caused by deforestation, or changing rainfall patterns resulting from climate change.

Resilient communities are characterized by economic diversity, reliable infrastructure, and strong institutional networks. However development, at its most basic level, begins simply with access to clean water, sanitation, and housing. Meeting these fundamental needs unlocks human potential, restores dignity, and enables people to go about their day-to-day activities, to generate social networks and business opportunities, and to progressively create the social, physical and economic infrastructure that in turn fuels further development and brokers the relationship between people and their environment.

To mark Arup's 60th Anniversary in a way that reflected the firm's values, the Arup Cause was initiated to motivate staff across the Arup world to recognize the beginning of this development cycle and contribute their skills, energy, and time to helping others.

A key part of this was a partnership with WaterAid. Over £80 000 was raised for WaterAid projects in Nepal and Nigeria that have provided clean water for life to 8000 people. Several staff members also had the opportunity to respond to particular needs and participate directly in WaterAid's country programmes in Bangladesh, Zambia, and Madagascar. In addition, the Arup Cause has supported other projects where staff have provided hands-on assistance to community-based projects in more than 15 countries. These include surveying a Buddhist monastery in West Bengal, developing clean water technologies in Ghana, Chile, and Thailand, advice on housing in Biloxi, New Orleans, after Hurricane Katrina, and supporting the construction of children's homes in Uganda and Sri Lanka.

What they have contributed goes well beyond technical analysis and advice; it has been about identifying the key issues and solving technical problems with a holistic perspective that takes account of social, technological, environmental, economic, and political parameters.

The three following articles give a flavour of this, detailing how Arup staff have contributed to reconstruction in Pakistan following the devastating 2005 earthquake, providing power through a mini-hydro project in Zambia, and helping to identify solutions to supplying safe water in Bangladesh.

**Jo da Silva** is an Associate Director at Arup, and leads Arup International Development which provides a focal point for Arup's work in developing country contexts. She is also a member of the Arup Cause Steering Group.

**Credits**

Illustrations: 1 Kubilây Hiçyılmaz; 2 Nadia Georgiou/Arup

**Key to map**

**SV: Supporters' visit**
1 Burkina Faso
2 Northern India

**FP: Funding project**
1 Nepal 1
2 Nigeria
3 Nepal 2

**PP: Pilot project**
1 Zambia
2 Bangladesh
3 Madagascar

**EP: Education project**
1 Leeds Water Action Day, UK
2 Conference attendance, UK
3 Conference attendance, Australia
4 Conference attendance, Sri Lanka

**HOP: Hands-on project**
1 Clean water supply for Karen hill tribe, Thailand
2 Filtration technology research, New York and Ghana
3 Agape orphanage and university course, Uganda
4 Akkaraipattu orphanage art therapy project, Sri Lanka
5 Zengamina hydroelectric dam, Zambia
6 Earthquake-resistant construction training manual, Pakistan
7 Skills centre construction supervision, Uganda
8 Engineers without borders, national training conference, UK
9 Loughborough University student sponsorship, Ethiopia
10 International Development Enterprises UK (IDE-UK) Annual Review, UK
11 Community Service Volunteers (CSV), UK
12 Partnership Overseas Networking Trust (PONT) mosquito nets, Uganda
13 Nezi Gompa survey, West Bengal
14 Global Vision International (GVI) Wasini Island, Kenya
15 Gorom-Gorom dam failure, Burkina Faso
16 Coastal desert fog harvesting, Chile
17 Post-earthquake reconstruction, Pakistan
18 Water and sanitation services to a school, Ladakh
19 Gulf Coast model home program, North America.

2. Arup Cause projects.

# Earthquake engineering training, Kashmir

**Kubilāy Hiçyılmaz**

2. Steel fixing with seismic detailing.

### Background

The South Asian earthquake of 8 October 2005 took over 80 000 lives. This was primarily because, as with so many previous earthquakes, the built environment in the affected area could not resist the loads to which it was subjected.

The only long-term remedy for such disasters is to rebuild safer communities. This region in Pakistani-administered Kashmir is not heavily developed and the scale of this particular tragedy was largely due to inappropriate construction and maintenance of housing, rather than any lack of political stability, money, food, or healthcare.

As part of Arup's policy to provide technical expertise to help NGOs to respond in the aftermath of a disaster, the author took a three-month secondment to work with GOAL, an aid agency contributing to the relief effort. During this time, he implemented a mobile training programme in earthquake-resistant construction, which was delivered directly to the affected communities by travelling to each of the six local Union Councils in GOAL's allocated areas of responsibility.

Each week around 50 experienced craftsmen took part in a four to five-day training programme.

1. Practicing building layout.

A mixture of classroom training and practical workshop sessions was used to alert them to aspects of building specifically to improve resistance to earthquakes.
At each location training was also provided for the general public. This consisted of one-day classroom-based workshops with site visits to inspect construction work carried out by the craftsmen earlier in the week.

### Who needs to be trained?

Engineers have to be able to do calculations, implement designs, and check the work on site. Builders need the knowledge to select materials of appropriate quality and apply high levels of workmanship to ensure robust construction. However, it is equally important that community leaders and decision-makers are educated about the consequences of not implementing earthquake-resistant construction, and that homeowners themselves learn what to look for in an earthquake-resistant house.

Ideally all those who have a stake in the built environment should receive training in disaster awareness and earthquake engineering, but the initial target for training has to be to those who actually do the building such as local craftsmen who typically act as designers, contractors, and labourers.

### Who builds houses?

In many developing regions, the built environment is assembled by local small contractors and self-builders using a limited number of skilled craftsmen supplemented by unskilled labour, rather than by degree-educated engineers and contractors with sophisticated tools and machinery who supervise a relatively well-trained construction workforce. Although isolated larger structures or industrial facilities will usually have some formal engineering input, typically the housing stock will not. Houses are therefore often very vulnerable to earthquakes, particularly where new construction methodologies, such as reinforced concrete, have been introduced in recent years and in particular where villages and towns have expanded rapidly. Often well-built traditional forms of construction have empirically incorporated earthquake-resistant details as building practices have evolved and responded to failures in previous events.

### How are house-builders trained currently?

In a region like Kashmir, those engaged in construction are generally craftsmen; masons, carpenters, steel fixers and shutterers, as well as labourers, who have all learnt their trade by observing their elders. They will often receive no formal education in these occupations and almost certainly no specific earthquake-resistant construction training. Often children start to learn about their future trades by going to work with their fathers or other male relatives, initially doing menial tasks and gradually adopting increased responsibility with age.

The learning process is passive; by observation initially and then by doing. Young people are not permitted to question the master craftsmen openly and those with the skills are not accustomed to actively passing them on. As a result, this form of training through apprenticeship is largely informal, uncontrolled, and often inadequate.

### Training material

Earthquake-resistant construction training, especially for a population with a relatively low level of formal education, is not straightforward and must be tailored for the specific audience. Textbooks, academic papers, building codes, and guidelines assume a level of formal educational literacy. Such training material as manages to filter through is not readily understood even by many who claim to be engineers. The material compiled for use after the Kashmir earthquake, therefore, had to be clear and as practical as possible. *PowerPoint* slides accompanied by practical hands-on workshops proved to be an effective medium.

In seismic areas not recently affected by earthquakes, training in earthquake-resistant construction must begin with raising awareness as to the impact and likelihood of earthquakes so that craftsmen and communities can appreciate why it is important. They may then take a view of the risk posed by earthquakes, and therefore the money and effort they are prepared to expend on earthquake resistance, compared with other risks and priorities.

### Training topics

The training programme that was developed was modular (Table 1). Introductory topics 1-6 and 8 apply to all stakeholders and are potentially the most important, as they set the scene for building safer communities in earthquake-prone regions. Topics 7-12 are more relevant to craftsmen, focusing on critical elements of good practice in design and construction, and how quite small changes to local building practices can significantly increase earthquake resistance. Presentation material was reinforced through practical workshops. Topic 13 is important in the aftermath of an earthquake for identifying the level to which buildings are damaged and unsafe, as they may be vulnerable during aftershocks. Which can be used? Which need repair or demolition? Topic 14 is a participatory approach to identify the vulnerability of existing structures and propose remedial works to improve them. Topic 15 is intended to provide a different approach to raising awareness of vulnerability, by encouraging people to look critically at their built environment, and themselves then decide how they wish to reduce the risk of future earthquakes.

Table 1. Initial training topics.

| First draft stage | | Works in progress | |
|---|---|---|---|
| 1 | Historic earthquakes | 9 | Brick masonry |
| 2 | Myths | 10 | Stone masonry |
| 3 | Plate tectonics | 11 | Confined masonry |
| 4 | Earthquake size and structural performance | 12 | Reinforced concrete |
| 5 | Site selection | 13 | Damage assessment |
| 6 | Building configuration | 14 | Assessment of undamaged buildings |
| 7 | Timber | 15 | Vulnerability tours |
| 8 | Technology transfer | | |

3. Course participants with assembled seismically detailed reinforcement cage.

4 Classroom education about earthquake basics.

5. Demonstrating the concept of bracing.

### Building capacity

Training those who are in a position to train others is also important, and to this end the author delivered the programme to staff from national and international NGOs, initially to the National Rural Support Programme in Islamabad, and later to Medair, ARC, Concern, Church World Services, Dosti, Save the Children, and World Vision. More programmes were carried out hosted by Mercy Corps and Architecture for Aid. All this showed the importance of transferring knowledge to those who need it most and the benefit a single technical expert can bring by translating knowledge into a manner that is readily understandable.

After returning to the UK, the author obtained support through the Arup Cause to initiate development of the training material so that it can not only be readily available for future use in this region, but also be easily adapted to reflect local culture and construction practices in other regions. Since it covers both earthquake awareness and construction, it has the potential to raise awareness and promote safer construction methods, and thus help to prevent a future disaster.

**Kubilây Hiçyılmaz** is a senior engineer with Arup in the Advanced Technology and Research London group.

**Credits**

**Illustrations:** 1-5 Kubilây Hiçyılmaz.

# Water supply options for saline areas in Bangladesh

Nicholas Swain

### Background

Satkhira, on the coast of Bangladesh, is one of the country's least developed districts. Predominantly rural, its communities are dispersed in small clusters, with widespread poverty and low literacy levels. The social structures are traditional, with limited opportunities and freedom for women. Traditionally, Satkhira's people have relied on agriculture for their livelihoods, with rice the main crop, but the explosion of shrimp farming in the last 10 years has brought changes to the economy, with many having to find alternative sources of income such as employment on shrimp farms, manual labouring, and petty trading.

The land is flat and low-lying, with an annual rainfall of around 2m. There is a monsoon season from May to October and a dry season between November and March. Cyclones can occur at the beginning and end of the monsoon but flooding is not a particular risk. The area is underlain by a shallow (20-100m) and a deep (c320m) aquifer, separated by a more or less continuous 10m clay layer. The shallow groundwater quality is variable across the district, with arsenic and salinity being problems in some areas; the deep groundwater may also be contaminated by salinity. Surface water bodies dominate the landscape, including tidal rivers, shrimp ponds, rice paddyfields, and domestic ponds used for fish farming, bathing, washing utensils, and drinking.

Availability of sweet (ie fresh) water is limited in Bangladesh's coastal areas. This has always been a problem due to saline intrusion from the sea, and recently the problem has moved further inland due to reduced river flows, construction of river embankments, and the proliferation of salt water shrimp farms. In some areas sweet groundwater is available but it is contaminated by arsenic.

1. Pond sand filter.

### The investigation

As part of the Arup Cause, and with WaterAid Bangladesh (WAB), Arup investigated water supply options for vulnerable communities in Satkhira, with the agreed objectives of:

- assessing the current supply situations and challenges
- identifying technical solutions, including the potential for desalination technology, and
- providing recommendations on further development of appropriate solutions.

A multidisciplinary Arup team was assembled in November 2006, with specialist knowledge of water and sanitation in developing countries as well as experience of working in Bangladesh. The team initially undertook a desk study to collate and review existing background data, and then two members made a 10-day study trip to Bangladesh, with logistical support from WAB. They met government agencies, NGOs, state donor organizations, and academic institutions, and took a four-day field visit to several communities in Satkhira.

Next, the team undertook a social, technological, economic, environmental, and political (STEEP) assessment of water supply options.

### Important considerations

The study trip and review of published information identified several important considerations when assessing water supply options, including:

- social factors such as individual preference and motivation
- availability (or not) of skills to build and maintain technologies
- limited availability and poor reliability of electric power supplies
- limited understanding of groundwater systems (hence uncertainty whether deep tube wells can provide long-term safe water)
- climate impact, eg movements of people and goods restricted in the monsoon season, and cyclones damaging infrastructure
- existing sweet water ponds at risk of turning saline due to shrimp farming, or being appropriated for other uses
- limited financial resources, leading to a preference for low-cost technology
- difficulties in managing community-based schemes: household schemes are the most successful to date.


2. Rainwater harvesting system.

### Assessing water supply options

Many areas are not close to sweet water and people may travel up to 5km to obtain supplies. The further away these sources are, the more people tend to use closer but less safe ones. Surface ponds or groundwater, though used for bathing, washing, and even cooking, are often contaminated. An alternative widely adopted in the 1970s was shallow tube wells, but in the 1980s arsenic was discovered in them as well, so people either progressed to deep tube wells or back to the ponds, now using their own pond sand filter technology to clean the water. Choice has thus been based on a hierarchy of cost and complexity. Relatively infrequently, households purchase water from vendors or use rainwater harvesting.

Where only saline water sources are available, the potential options for a convenient supply appear to be rainwater harvesting, reverse osmosis, solar distillation, or water piped from elsewhere.

Rainwater harvesting) is well suited to these areas of relatively high rainfall, and has been enthusiastically accepted by households where arsenic poisoning has occurred. It has the advantage of being relatively simple technology, but some obstacles exist including marginal affordability, dislike by some people, and risk of loss of supply during the dry season. Also, a lack of builders has limited its adoption.

Reverse osmosis desalination is a well-proven technology able to convert saline water sources to sweet water, but several significant barriers exist, notably cost, reliability of power supply, and availability of the required technical and managerial human resources. On a large enough scale, reverse osmosis can be a lower-cost option than household rainwater harvesting; whether it is more cost-effective than a piped supply depends on the length of pipeline needed.

Solar distillation is potentially attractive, being theoretically simple technology that requires no purchase of energy, but it is not yet well developed and no affordable or suitable commercially available systems were identified. With its drawbacks of low output and high cost, it may be more suited as an emergency or supplementary system, and work is needed to develop an affordable and robust device.

Rainwater harvesting appears to be the preferable option if a low complexity system is required, but whichever technology proves to be the most appropriate, the development of water supplies in the area will need to consider future population growth and possible changes to climate.

### Recommendations

In its report to WAB in February 2007, Arup recommended that to support future decision-making, knowledge of existing sweet water supplies should be developed. Modelling the deep aquifer would give better understanding of supply sustainability in terms of both quantity and quality. Surface water pond risk assessments and rehabilitation strategies should also be developed.

It was also recommended to develop potential supplies for saline areas by the continued promotion and improvement of rainwater harvesting systems, assessment of piped water supplies, and development of appropriate reverse osmosis systems. The latter would require:

- collection of relevant water quality data
- feasibility studies including concept designs, cost estimates, identification/development of the institutional framework needed, stakeholder consultation, and comparisons with rainwater harvesting and piped supply
- design and implementation of demonstration systems at a selected site or sites.

**Nicholas Swain** is an Associate of Arup in the Water (Australia) Group based in the Adelaide office. He has a developing interest in the political, economic, and environmental aspects of water and wastewater schemes.

**Credits**

**Illustrations:** 1 Nicholas Swain 2, 4, 5 Arup
3 Kabita Yesmin, WaterAid Bangladesh

3. Traditional method of obtaining water.

4. Pump from tube well.

5. Reverse osmosis equipment.

1. Not everything can be done by manpower - dragging the 700kW turbine for installation in the powerhouse.

# Zengamina 700kW hydroelectric scheme, Upper Zambezi River, North West Zambia

Daniel Rea  Ewan Walker

### The need

This province of Zambia struggles against classic factors in the cycle of poverty. With little education, employment, or prospects, the local people struggle from day to day against malaria, HIV/AIDS, and malnutrition. They exist by slash-and-burn subsistence farming, and as the population has grown in the last 100 years, so the environment has degraded. There is an established local hospital and secondary school, but lack of electricity, or reliance on intermittent and expensive diesel generators, has limited their services. With the national grid 380km away, another solution was required. In colonial times – 42 years ago - a hydroelectric site on the Zambezi River only 6km away was surveyed, but until now it had not been developed.

### The solution

The project is named after the local chief, His Royal Highness Chief Zengamina Nyakasaya (recently deceased), but the instigator and client is the North West Zambia Development Trust (NWZDT), a charity set up by people connected with the area, both local and in the UK. Working directly with the local population, and with a connection to the historic Kalene mission hospital which celebrated 100 years of service in 2006, it believes that while many individual crises can be eased by food and medicine, real progress comes from investment in infrastructure that most in the West take for granted - clean water, electricity, sanitation, and employment. A source of sustainable electric power was judged the priority as a trigger to the others, and NWZDT worked with a local contractor to build it at cost.

The project's success is down to the determination of the core team and a remarkable mobilization of freely-given expertise and goodwill from around the globe – from transmission cables and equipment donated from Sweden, to worldwide technical expertise, including World Bank consultants, to local fabricators working at cost only.

Funding is almost entirely by private donations in the UK, and fund raising has been in parallel with progress, regularly testing faith. Once completed, the project will operate as a private utility company, with revenues from the sale of power making it a self-sustaining enterprise that can expand in future. The NWZDT is the primary shareholder and any future dividends will be used for other developments in the area. There are rural electrification initiatives across Africa, and the NWZDT is working with the Zambian government to extend further the grid to serve a wider area.

The feasibility study was completed in 2003, initial site clearance began in 2004, and construction started in earnest in April 2005. Independent personal connections to NWZDT led to requests for help with on-site construction supervision. Under the Arup Cause banner, the firm agreed to Daniel Rea taking 12 months' unpaid leave of absence for this voluntary role, during which time most of the civil works were completed (2005-06). The key civil works elements were designed by Belfast-based firm Ferguson McIlveen (now Scott Wilson), but significant design and design development were done on site.

### Scheme overview

The mighty Zambezi, famed for the Victoria Falls, is a small river here, its source only 50km away. It flows over a granite dome, falling about 17m through c350m of rapids. The site catchment and mean annual rainfall of the area are around 600km$^2$ and 1500mm respectively. The minimum flow in the river in November is c4m$^3$/sec, but at peak in late March it is estimated to be >300m$^3$/sec (!). The water travels via a canal to a penstock to the turbine in the powerhouse. The civil works had to:

- be environmentally and aesthetically acceptable
- pass the maximum volume of water, which at times floods low-lying adjacent areas, without sustaining damage
- divert and transport sediment through the off-take structures
- minimize head loss through the system so as to maximize power generation
- ensure safe human occupancy in the area
- be durable with minimal maintenance
- accommodate the future addition of another turbine to increase capacity.

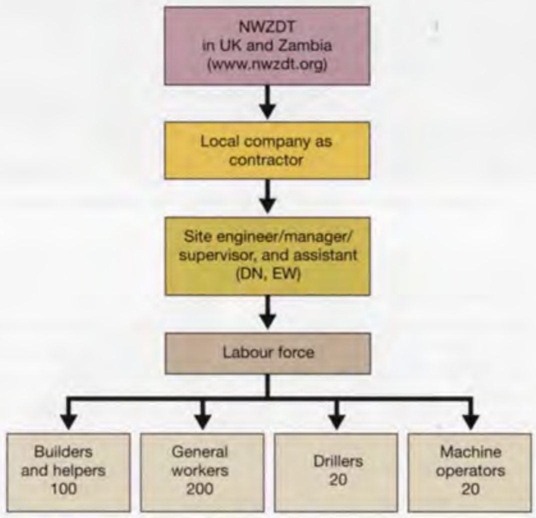
The civil elements - the weir, canal, headpond, and powerhouse - are mainly of rough stone masonry with mortar. The primary building material was thus the granite blasted on site for the canal and powerhouse sump - a huge saving on materials and transport costs, as well as efficient use of natural resources. The NWZDT chose to use labour-based construction and avoid machinery so as to increase local employment - 99% of the workforce was unskilled labour from nearby villages, 40% of them women, many in their first formal employment. Reinforced concrete was used for specific structural elements, again with site granite as aggregate so that only steel and cement were transported in.

Various turbine designs suit different conditions of water head and flow, as well as user demand, so selecting the appropriate type for the project was the most critical single decision. A cross-flow turbine was chosen as it gives the best dependability over a range of demands, as happens with an isolated grid. The German company Ossberger was chosen for its long and proven history of top quality, durable, and well-engineered turbines. To minimize losses, transmission will be at 33kV, with step-down transformers at nodes along the way.

Overall construction value of the civil works, electromechanical equipment, and transmission lines is around £1.3M, aside from very significant donations of expertise and equipment. During construction, the cost of raw materials increased 100-200%, the Zambian currency strengthened by 40%, reducing the funds raised in the UK by the same, new labour laws trebled wages, and there was a national fuel crisis. However, the project was completed for only 10% over the 2003 feasibility study estimate of £1.2M.

2. Lifting major building elements without cranage: the powerhouse under construction.

3. The powerhouse under construction.




4. Project organization structure (numbers at peak).

### Constraints and challenges

It is impossible to convey the challenges of building a large and technical construction project 600km down a bumpy road from the nearest supplies, with no telephone or internet, a largely unskilled and illiterate workforce, and an incomplete design – all in a foreign language and culture, whilst living in a tent and eating local bushmeat and maize meal every day. Suffice to say that each day was filled with many and sometimes unique challenges – the greatest being the need for absolute flexibility, matched with good organization and strong leadership to ensure progress was made. Close behind were the resourcefulness and determination required to overcome regular and seemingly impossible obstacles – a "need a crane, make a crane" mentality.

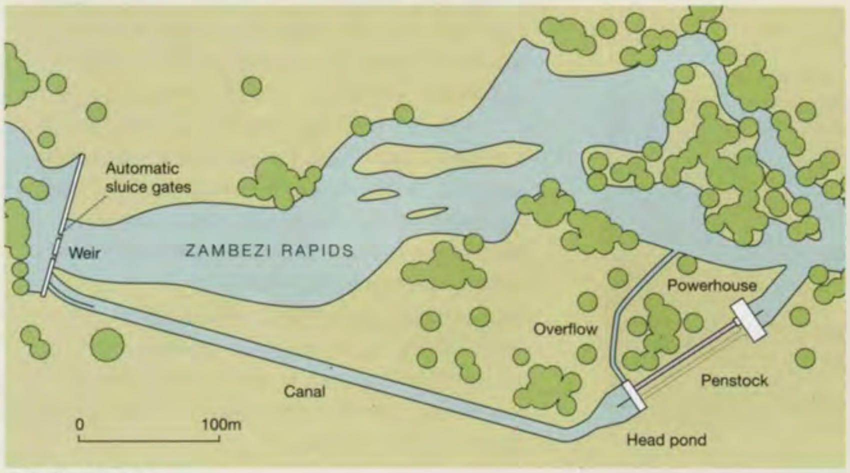
5. The weir under construction, showing the automatic sluice gate in the centre, and fitting gate channels to the entrance to the canal in the foreground.

## Small hydro power

International organizations see increased access to electricity as a major driver in reducing poverty. Power can stimulate and improve rural communities, with health, education, employment, trade, pumped water, and night-time lighting all benefiting hugely from electricity – all linked to UN millennium goals.

Although fairly expensive to install (averaging approximately US$2000-$3000/kW), small hydroelectric power has many advantages over alternative energy sources for rural areas. It is far cheaper and more useful than photovoltaics as it can run machinery, be used for cooking, etc. It suits communities remote from the grid (rural electrification in Africa is minimal), has minimal maintenance requirements or costs, is a proven technology, and is reliable. Raising the initial capital is the main challenge.

Significantly, it also does not have the negative environmental or social impacts of the storage dams of large hydro schemes. Small hydro schemes (typically 300kW- 5MW range) are usually "run-of-river", ie they utilize a weir that diverts only part of the river, which immediately rejoins the main flow after passing through the turbine. This means a negligible area is flooded, minimizing impact on the river ecosystem and avoiding relocating people, and only a very short section of river experiences any change in flow.




6. Project layout.

### Conclusion

The dam was officially opened by the Zambian Energy Minister (in lieu of the indisposed President) on 14 July 2007. Immediately the project is bringing lighting and electricity for the first time to hundreds of villagers, but its impact will be far wider. People walk 100km and more from Zambia, Angola, and the DR Congo to the hospital, which now has 24/7 power. A few days before the opening, doctors carried out the first-ever operation under general anaesthetic - possible only by the availability of reliable power. The local secondary school is being refurbished and will be able to attract staff. Local businesses are setting up in readiness, and people are investing in their houses. It is a remarkable and inspiring example of can be achieved by what started as a vision and a few thousand pounds.

**Daniel Rea** is a chartered engineer with Arup in the Project Management London group. He has developing interests in sustainability, urban design, and work in developing countries. In the Building Awards 2007, he won the Construction Skills Achiever of the Year Award largely for his work on the Zengamina project.

**Ewan Walker** is a graduate mechanical engineer in Arup's Buildings London 4 Group. After graduating from university, he spent a year on site as a volunteer and then joined Arup.

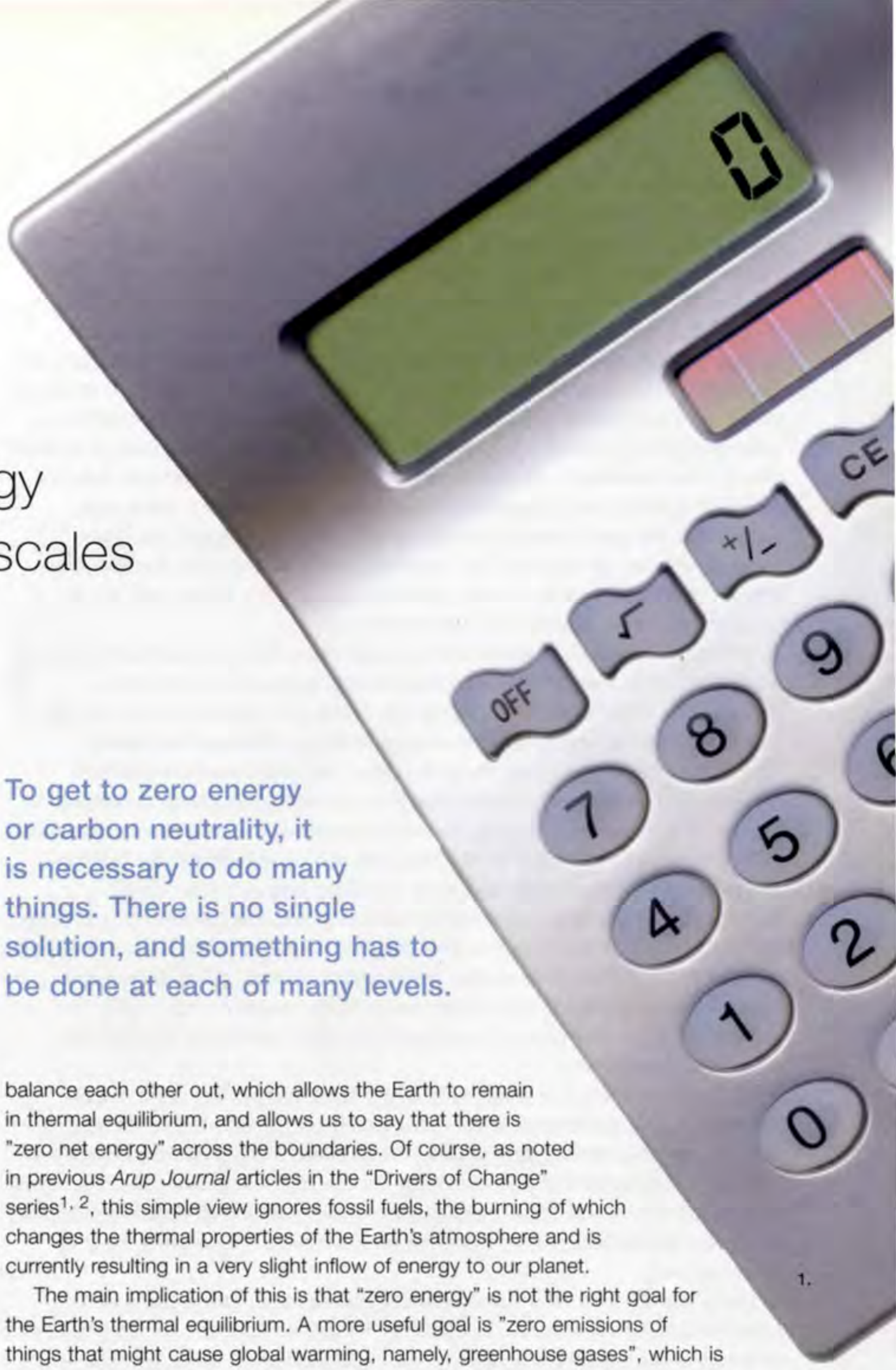
**Credits**

**Illustrations:** 1-3, 5 Daniel Rea; 4, 6 Nigel Whale.

# Down to zero!

## Understanding zero energy and zero carbon across scales

Fiona Cousins



1.

**Zero energy, zero carbon – What's the goal?**

There has been much talk of "zero energy" and "carbon neutrality" over the last few years, but there is not yet consensus about what these terms really mean, or why setting them as targets for individual projects or as enterprise goals for firms or other corporate bodies is important. This article sets out to explain what they mean, their implications, and the measures that have to be taken to achieve them, specifically at the level of the built environment. As the built environment is our main user of energy, the measures needed to get to zero energy or zero carbon for the built environment are often the same as those required at enterprise level.

The first thing that becomes clear is that the definition of "zero energy" changes as you move the physical boundary within which you are trying to achieve it. For example, imagine that you are sitting at your desk, and the boundary within which you are trying to achieve zero energy is formed by your office or cubicle walls, its ceiling, and its floor. The energy users are the lights, the computer and monitor, and maybe the heating, cooling, and ventilation systems. You might be able to achieve zero energy transfer across the boundary of your office for a short period by installing a stationary bicycle and pedalling hard enough to generate all the power for these systems. But of course as soon as you become hungry you will need to leave the confines of your office and find something to eat. Your return from your lunch break will bring a net in-flow of energy to the system.

At the opposite extreme, draw the boundary around the world. Energy flows continuously to and from the Earth, through radiation inwards from the Sun and outwards to the atmosphere. These flows balance each other out, which allows the Earth to remain in thermal equilibrium, and allows us to say that there is "zero net energy" across the boundaries. Of course, as noted in previous *Arup Journal* articles in the "Drivers of Change" series[1, 2], this simple view ignores fossil fuels, the burning of which changes the thermal properties of the Earth's atmosphere and is currently resulting in a very slight inflow of energy to our planet.

> **To get to zero energy or carbon neutrality, it is necessary to do many things. There is no single solution, and something has to be done at each of many levels.**

The main implication of this is that "zero energy" is not the right goal for the Earth's thermal equilibrium. A more useful goal is "zero emissions of things that might cause global warming, namely, greenhouse gases", which is usually abbreviated to "zero carbon". Emissions of global warming gases are normally measured in terms of their relationship to carbon dioxide ($CO_2$) emissions, so that "zero carbon" is short for "zero carbon dioxide equivalent emissions". In our small-scale example, the metabolic burning of lunch leads to $CO_2$ emissions in the breath, so this "zero energy" scenario is not a "zero carbon" scenario.
At the scale of the built environment, we might draw the boundary at the building perimeter, and it is difficult to find a building that can be considered "zero energy" as defined above. Almost all buildings receive sunlight during the day and re-emit the energy as heat overnight. At any given time, energy will be crossing the building boundary. However, unserviced buildings such as daylit barns and sheds can be considered "zero net energy" because the total amount of energy absorbed and the total amount radiated are the same over time. Such buildings can certainly be considered as "zero carbon" for their operations.

Another way to achieve a "zero carbon" building is to allow the building to use energy but to eliminate operational $CO_2$ by providing energy from non-carbon sources such as wind or the Sun. For most multi-storey buildings, the size of the required renewable energy harvesting installation is much larger than the building area, and renewable energy technologies tend to be expensive compared to connections to local energy supply grids. Also, solar and wind energy are not always available when they are needed. One approach that allows a building to be "zero carbon" is to install a very large renewables installation and to store energy for when renewable power is not available. A second approach is for the building to draw energy from a local supply grid that is likely to use some fossil fuel to generate power, when necessary, and to sell carbon-free power back to the grid when the renewables installation is generating more power than needed. If the energy exported to the grid is equal to the energy imported from the grid, such an arrangement may be described as "zero net carbon" on the basis that the power exported to the grid will allow less fossil fuel to be burned. A zero net carbon project can also be described as "carbon neutral".

The idea of connection to the electrical grid raises one more boundary issue, and highlights another difference between energy and carbon as metrics for performance. If fuel is delivered directly to a building, for example as natural gas or diesel, the "source" energy and the amount of energy crossing the building boundary, or "site" energy, are about the same. But when electrical energy is delivered to a building, only a small proportion of the source energy is delivered to the site. This is because, typically, fossil fuel power stations convert only about 30-40% of the energy in the fuel to electricity that can be delivered to the building. The remainder is lost as heat, and some additional energy is lost during transmission. This means that the electrical energy and fuel delivered to a building cannot be directly added together and assumed to represent the carbon emissions. Unless the electricity is from nuclear or renewable sources, a building's carbon emissions generally relate much more closely to the source energy than to the site energy, which strengthens the argument for using carbon as the preferred measure of performance.

At a regional scale, it is tempting to define "zero energy" and "zero carbon" with reference to buildings only, but this is clearly not the only factor, although building carbon emissions tend to dominate in dense urban environments (in New York, for example, 69% of $CO_2$ emissions are due to buildings and only 23% due to transportation[3]). At this scale, transportation energy use and its associated carbon emissions, as well as the energy and carbon associated with industry, need to be considered.

Up to this point we have considered only "operational" energy use and associated carbon emissions. Constructing the built environment uses a great deal of energy in the manufacture, delivery, and installation of materials, however, and additional energy is used in the deconstruction and disposal of built environment at the end of its useful life. The energy used in these processes, and the associated carbon emissions, are known as "embodied energy" and "embodied carbon".

All these factors mean that the appropriate goal for a project or enterprise is more closely related to carbon than to energy *per se*. Zero carbon emissions increase for the built environment as a whole is a reasonable goal for the future if greenhouse gas concentrations are to be stabilized, and it will most easily be achieved through a combination of low carbon design for new buildings and the reduction of energy consumption in existing buildings.

**Who controls zero?**

Just as the important components of energy use and carbon emissions vary with different boundaries, so too do the responsibility for and control of those emissions.

Reverting to our original office model - and assuming that the building owner has provided the means to generate power at the desk - the only person who can determine how much power is generated is the worker, who can choose to pedal faster or slower, to complain about working conditions, or be content. At the whole building scale, the building owner and design team can influence the way energy is used within the building through design, but can only slightly influence the mix of sources used to generate electricity by the regional utility. A single building owner cannot significantly change the amount of greenhouse gas generated by the utility.

At the regional or national scale, the amount of carbon generated is controlled by government - through legislation, transportation and energy policy, and incentives - and (less strongly!) by commerce, through purchasing decisions. In other words, it is controlled by voters and public opinion, but it is has not yet become a key election issue. At the global scale, the only groups that might be able to influence the use of energy or generation of power are supranational bodies like the United Nations or the World Trade Organization.

2. In New York, 69% of $CO_2$ emissions are due to buildings and only 23% due to transportation.

**The case study**

The ideas of "zero energy" and "zero carbon" are beginning to make it into the mainstream, and it was perhaps symptomatic of this that Arup was asked in 2006 by *Architectural Record* magazine to design a hypothetical "zero energy building".

The team decided to model a generic, mixed-use building (Fig 3) in Houston, Texas, choosing this location because of the hot, humid climate. This is challenging from the energy standpoint because the building systems have to work hard almost all the time to keep the occupants comfortable. It is much easier to get buildings to run without fossil fuel in climates where winters are warm, summers are cool, and night-time temperatures are moderate.

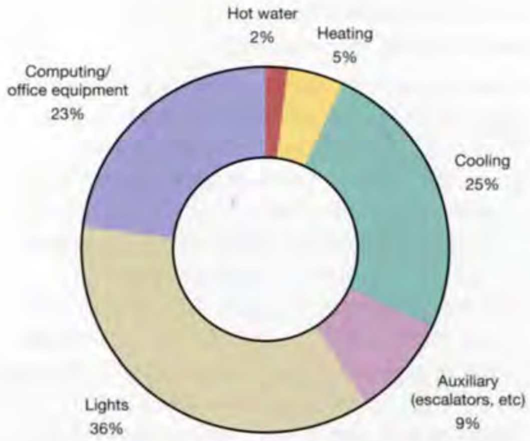
The building was also imagined as being large, though on a small site. Small buildings on large sites are easier to power with renewables because the development density is lower. However, they account for a much smaller proportion of the building stock, are rare in urban areas, where most new building takes place, and don't meet the practical needs of most owners.

The building proposed is mixed use, with six storeys of parking, eight storeys of offices, and about 20 storeys of residential. Choosing a mixed-use project allowed the team to capitalize on complementary load profiles within the building*.

The gross areas are 350 000ft² (32 520m²) of office, 650 000 ft² (60 390m²) of residential, and 500 000 ft² (46 450m²) of parking garage. The building was modelled to match the types of buildings existing and currently under construction, on the basis that programme and financial considerations usually drive the building form far more strongly than energy use or the desire for views. It would be possible to achieve different results, and probably lower energy use, if the building were to be a different shape, with more façade and more opportunity for daylight, but this was not part of this study.

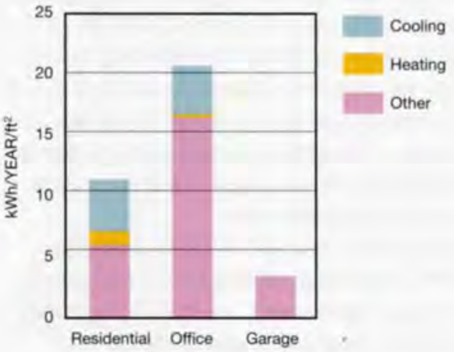
The base building was designed to be code-compliant by meeting the most up-to-date version of the US energy and ventilation codes, *ASHRAE 90.1-2004*[4] and *ASHRAE 62-2004*[5], and the energy analysis was carried out following the rules set out in the energy code. Office profiles were fixed for 8am to 6pm and there is a peak in the residential energy use in both the morning and the evening. The parking garage is shared between the office and residential users, and ventilation and lighting run continuously in the base case.

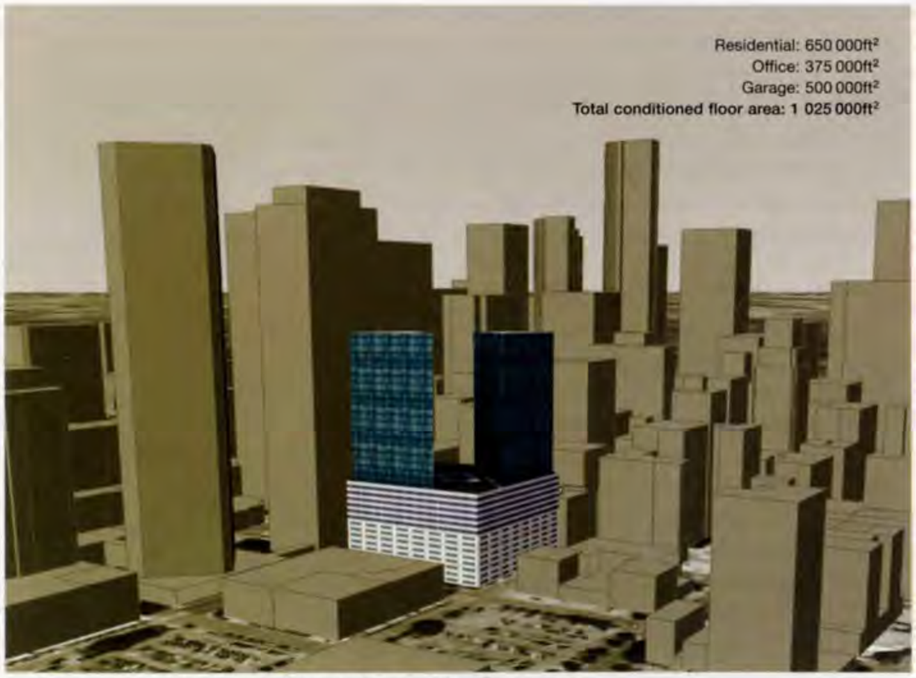
The first step was to analyze the building energy use over the course of a year, because to reduce energy use it is important to understand where the major energy uses are (Fig 4). The three major energy uses are lighting, miscellaneous equipment (ie "small power loads" in the UK and "outlet power" in the US) and cooling. Because the building has a deep floor plate, most of the cooling energy required is used to handle the internal loads and the fresh air requirements for the occupants, rather than solar gain. Heating energy is low, as would be expected for Texas.




4. Whole-building annual energy consumption by end-use.

5. Annual site energy consumption, by building type and end-use.




3. The generic mixed-use building in Houston, Texas.

The next step was to look at the energy use split across different uses. The residential floors have a higher proportion of heating load than the office space because the equipment and lighting uses are typically much less. The proportion of cooling and heating for the residential is also much larger because there is more façade area per amount of floor area.

The office energy use is driven by the lights and computer equipment and is by far the largest component of energy use for the whole building (Fig 5), even though the office area is only half that of the residential and has shorter occupied hours. The lower energy use per ft² in the residential spaces should not be taken to indicate that telecommuting is the most energy-efficient way to work, however, as the residential spaces were modelled as only lightly occupied during the day.

The garage is not heated or cooled. Here, the energy use is for lighting and ventilation.

* In the real world it is more likely that complementary load profiles would be found by looking at a neighbourhood rather than a single building. The key difference is the amount of control each building owner has and the amount of co-operation that would be required between them. This is an example of the way control changes with scale.

## Energy use reductions and efficiency improvements

Having gained an understanding of the main energy uses, the team proposed several ways to reduce energy use. The initial strategies fell into two categories: reducing the loads and providing more efficient ways to meet them.

The biggest users of energy are the mechanical and electrical systems. Traditionally, US office spaces are served by overhead VAV systems that provide reasonable local control but require a great deal of energy to move large amounts of air through the building. Alternative systems, including underfloor air systems, which have a longer "free cooling" season (even in Texas) but still move a lot of air around, and chilled beam systems - which save energy by using water rather than air as the main means of transporting cooling through the building - were considered. There are many options and the best one depends on climate and building use. The present case study, because of its US context, uses an underfloor air system as there is some market resistance to water-based systems in the US, even though these improve the energy performance. It would be impossible to get closer to zero and still use an approach that most local clients would find acceptable.

In addition to systems that affect comfort in the rooms, it is also possible to make efficiency gains through "dedicated outdoor air systems with heat recovery" (particularly appropriate in the Texas/Gulf of Mexico environment), more efficient cooling towers, chillers and motors, economizer systems, and so on. The case study model uses all the most appropriate solutions for this climate and building type.

Loads can also be reduced through improving the building envelope because some of the energy use is related to solar gain and conduction through the façade. In a building of this scale, the energy use directly related to the façade is quite low because the floor plan is so deep, but there are still significant effects from shading, from placing glazing correctly, and from including good levels of insulation. Clearly, the façade design needs to be tuned to allow daylighting as well as to provide protection from solar gain and keep the heat (or coolness) inside the building.

One effect of insulation is that it can improve comfort in a particular area of the building, and reduce the energy use – in some climates it may even remove the need for perimeter heating or cooling, reducing the need for both operational energy and embodied energy in the form of additional systems.

As noted above, lighting is a significant energy user. One way to reduce this energy consumption is to admit daylight and provide controls that turn the lights off when the daylight is adequate. Another way is to install occupancy sensors to turn off the lights when no people are present. The effect of daylight is, however, quite small in a commercial building with a floor plate as large as this one, and the effect in the residential building is small because occupied hours frequently do not coincide with daylight hours. Lighting energy use can also be reduced through efficient sources and daylight savings. However, the energy code used as the basis for design has stringent lighting power limits that are close to the limits of available technology, so the effect of more efficient sources was minor in this analysis. In existing buildings, this change can represent a major saving.

The last major method of managing the energy demand is to alter the design conditions. Most buildings are designed to hold air temperatures at 22°C ± 1.7°C (72°F ± 3°F). Given the right clothing, it is possible for people to be comfortable between about 20°C (68°F) and 26°C (78°F). To reduce energy use, an owner/occupier could decide to set the design temperature to the former in winter and the latter in summer and require the occupants to dress appropriately. However, even if this change is made, most building operators will set the thermostat to 22°C (72°F), and given the rarity of design conditions, the system will still achieve 22°C most of the time, so there will be very little saving in energy. To capitalize on savings from a broader range of design conditions requires personal motivation. In theory this might be achieved through good education from the design team and building owner, but given the range of preoccupations of the average individual, including the primacy of his/her "comfort zone" in every sense, it is impractical to expect environmental responsibility to consistently and universally take precedence over self-interest. This is a clear instance where the control of energy use lies with the building operator and occupant and not with the designer or building owner.

Each bar on Fig 6a represents a different energy-saving measure, implemented cumulatively. Clearly no single measure will allow the building to achieve "zero energy", so the only way to reduce the site energy use is to attack on all fronts, including minimizing the run-time of equipment, buying the most efficient equipment possible, and providing heating and cooling in the most energy-efficient ways.

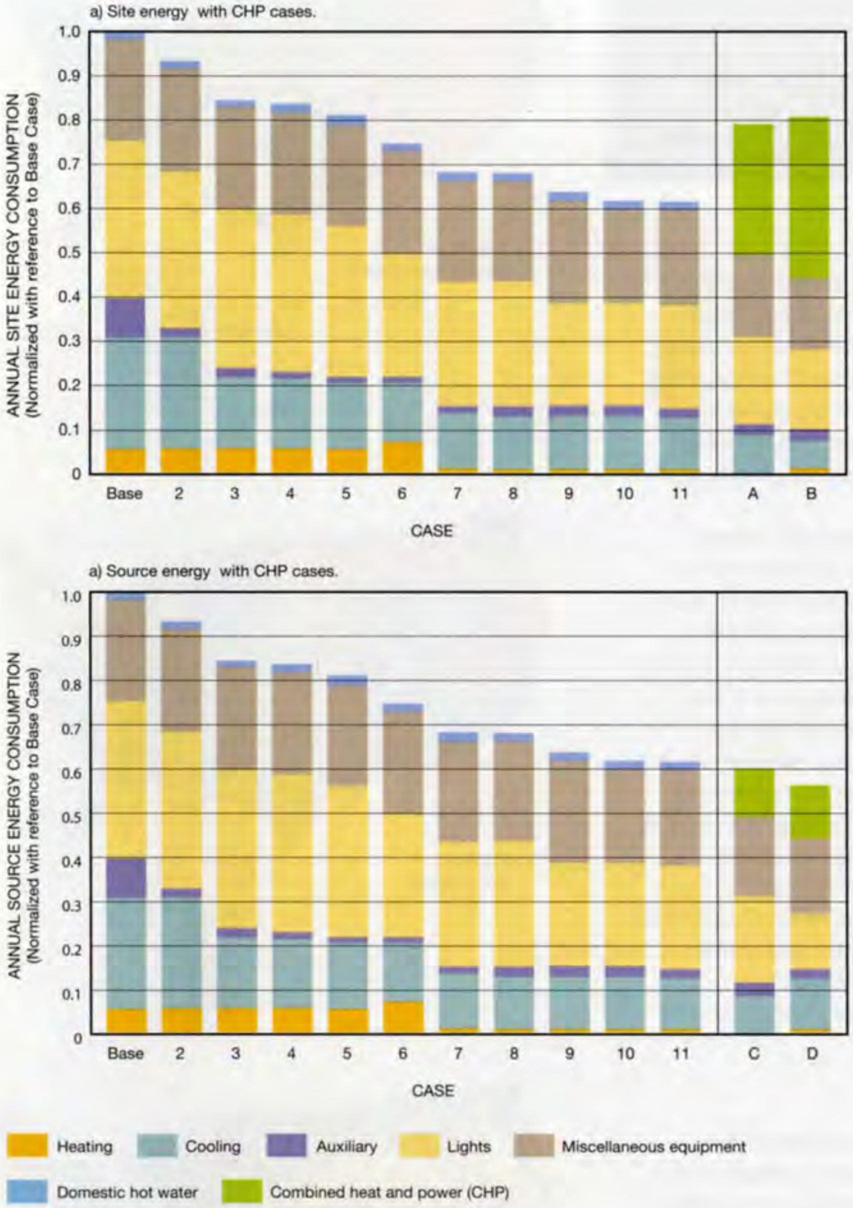
All the energy reduction and design measures get the building energy use down to about 60% of the code-compliant energy use. This represents about the lowest energy use that can be achieved using current technologies for this type of large and heavily-serviced building through demand side measures only.

## Source selection and $CO_2$ reductions

Once the energy demand has been reduced as low as possible, the next step is to consider more "carbon-efficient" ways to generate electrical power. The most common approaches are to use renewables such as solar and wind, or a combined heat and power (CHP) or cogeneration plant.

CHP plants can be implemented at the building scale or at the neighbourhood scale. The rules of thermodynamics dictate that when fuel is used to make electricity, a lot of its energy is converted to heat. If the power is generated remote from potential heat use, most of the heat is wasted and discharged to atmosphere, but if the power is generated close to potential heat use, then the heat can be utilized. Uses in a building include heating the building itself, heating domestic hot water, or providing cooling using a steam-driven absorption chiller or turbine-driven chiller. In Texas, the best use, during most of the year, is for cooling.

6. Impact of energy conservation measures on whole-building energy consumption. Because of the inefficiencies of converting fuel into electricity, more energy is consumed at the source than on site. However, the impact on both site energy consumption (6a) and source energy consumption (6b) of the various measures is proportionally virtually identical for this building and systems.




**Key to energy measures**

2. Use of natural ventilation in garage/Improved office fan efficiencies
3. Improved chiller/condenser/pump efficiencies
4. Use of underfloor distribution with economizer in office
5. Addition of more office lighting occupancy sensors/Addition of office daylighting
6. Use ofcompact fluorescent lamps in residential fixtures
7. Increased insulation levels/Improved glazing performance
8. Addition of energy recovery to residential ventilation
9. Addition of garage lighting timers and occupancy sensors
10. Use of ENERGY STAR (US government energy conservation guidelines) office equipment
11. Reduction of residential window-to-wall ratio

A. Use of CHP with residential fan coils and absorption chiller
B. Use of CHP with residential fan coils, steam turbine chiller and thermal energy storage
C. CHP with residential fan coils and absorption chiller in terms of source energy consumption
D. CHP with residential fan coils, steam turbine chiller and thermal energy storage in terms of source energy consumption.

Fig 6a shows the site energy reductions through all the energy-saving cases and then a large increase in site energy use when the CHP plant is added. This is as expected, because fuel use has been shifted from the electric power station to the site. If the source energy figures are examined (Fig 6b), the use of CHP leads to a reduction in the amount of fossil fuel used, and therefore the amount of $CO_2$ emitted.

The use of CHP, together with all the demand side reductions considered already, allows the source energy to be reduced to about 55% of the base building value. This is clearly not a "zero net energy" solution, but it is a significant improvement over the baseline and an even more significant improvement compared to typical existing building performance.

At this point there were no further ways to reduce the energy use, so the project team started to examine zero carbon solutions, of which the only ones possible in Houston are solar and wind energy (elsewhere in the world geothermal energy would be a possibility). Two solutions were tested in the energy model – one with two outsized (600kW) wind turbines on the building roof and one with PV (photovoltaic) cells on all the appropriate building surfaces.

These two measures, together with all the previous reductions, brought the source energy use to about 45% of the original source energy use. It would be possible to achieve "zero net carbon" for the building through the purchase of renewable source electric power from the utility and the purchase of off-sets for the fossil fuel power. However, the market for offsets is not yet robust because offsets standards have not been formally established[6].

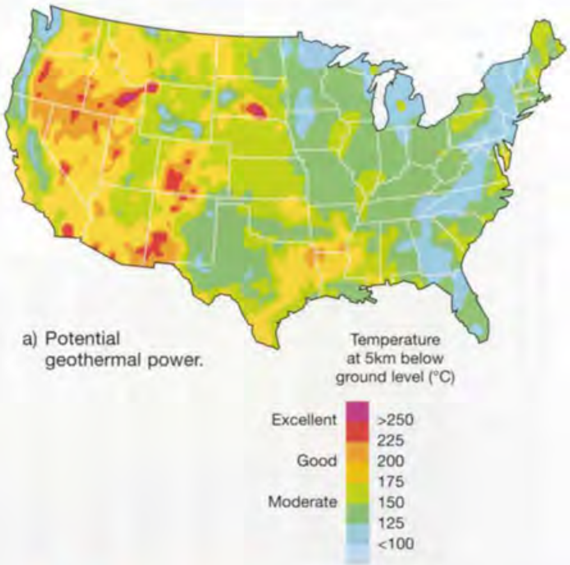
All the energy reduction methods discussed are controlled by the building design team, as is the use of CHP, but a coalition of buildings may be required for it to become economically feasible. The purchase of renewably sourced electrical power is also a choice that can be made at the building level. However, the provision of renewable power from other locations and the robustness of offsets are controlled by others, although the building owner can influence these through purchasing decisions.

### Regional and national scale renewables

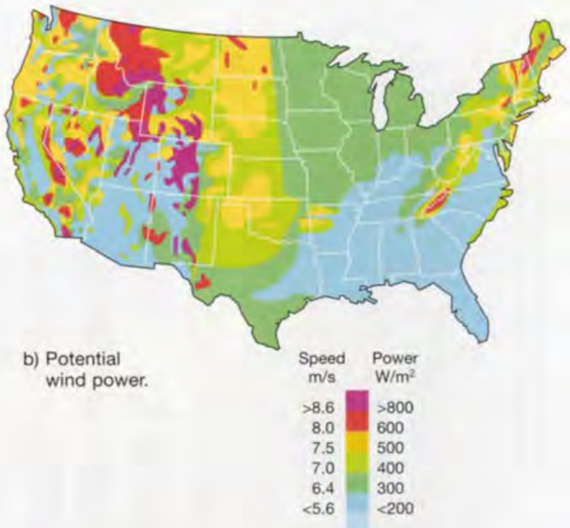
The Arup case study showed that it is very difficult to achieve zero energy and zero carbon at the site. One approach is to be zero carbon regionally. but this requires much more co-operation between building owners, and may also require regional government involvement, depending on the scale.

7. The major load centres in the USA and Canada.

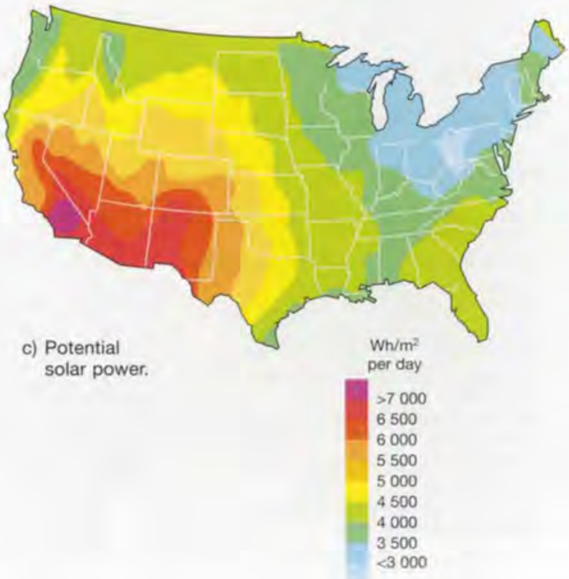
8. The best regions for renewable energy generation in the USA.




a) Potential geothermal power.




b) Potential wind power.




c) Potential solar power.

As an example of the issues involved, the major load centres in North America (Fig 7) may be compared with the areas with the largest potential for renewable energy generation (Fig 8). The best places for wind energy are on the coast and in the Rockies, for geothermal in the Rockies and along California's fault lines, and for solar in the South Western deserts. The differences can be quite pronounced: a wind turbine in Grand Island, Nebraska, will harvest twice as much energy as the same size turbine in Houston, and a photovoltaic array in Arizona will provide much more energy than the same size array in Minnesota.

Energy harvesting equipment tends to be expensive, so ostensibly it makes sense to put it in the places where it can harvest most energy, but if the buildings and the renewable power sources are not in the same place, enough transmission infrastructure needs to be built to connect the two together. This includes pylons, cables, and connection equipment, and can be both expensive and environmentally invasive to construct. In addition, power from wind and solar installations is not available all the time, and so the infrastructure also needs to include storage mechanisms that allow power to be stored until it is needed, using, for example, a pumped storage station. During times when there is more power than necessary, water is pumped uphill to a reservoir. When there is demand for energy, the water is run through a turbine and electricity is generated. Other potential alternatives include hydrogen generation, battery storage, and flywheel technologies.

The locations of renewable installations, therefore, need to be based on both the maximum output that can be achieved and the amount of infrastructure that is required to connect the renewable source to the existing transmission and distribution systems. The investment calculation can be performed using both financial and carbon measures.

### Embodied energy and embodied carbon

So far, the discussion has centered around operational energy and operational carbon emissions. As mentioned at the start, there are also carbon emissions and energy use associated with the manufacture, delivery, and installation of materials. Additional energy is used for deconstruction and disposal at the end of a building's useful life.

To establish the relative importance of these emissions, the Arup project team carried out one check calculation for embodied energy. The amount of embodied carbon associated with the production of half of the cement required to build the case study building was calculated. It is possible, under most building codes, to use an alternative material that is a by-product of power generation instead of part of the cement in concrete. Fig 9 shows that this one substitution saves an amount of embodied carbon equal to approximately one year's operational carbon emissions. Embodied carbon is clearly significant for both infrastructure and building construction, and becomes increasingly significant the shorter the building's proposed life.

In the same way that it is possible to carry out a life-cycle cost assessment for a project, it is also possible to carry out a life-cycle carbon assessment.

## Transportation energy use and carbon emissions

In the US, transportation accounts for approximately 40% of source energy use, and statistics from other developed nations are similar. Unlike electricity or heat, which can be produced from various different types of fuel, transportation is strongly dependent on oil, because it contains a lot of energy per unit volume and is therefore easy to transport.

Strategies for reducing energy use and carbon emissions follow the same pattern as those for reducing building energy use. Unlike building energy use, which is largely controlled by the owner and designers, transportation energy use is heavily dependent on the design of the local transport system and is therefore generally under governmental control.

How is it to be reduced? There are several strategies for doing this, including improving fuel economy through vehicle design, encouraging shared rides and the use of alternative modes, and reducing the distances that have to be covered. The efficiency of transportation energy use can also be improved by reducing idling time and ensuring that traffic flows well. The choice of vehicle and appropriate mode is in the hands of the traveller, but control over the provision of appropriate modes, including the design of urban environments to reduce transportation dependence and encourage good traffic flow, is much more widely dispersed.

A further strategy is to substitute fuels with lower carbon content. Ethanol from corn has lower carbon emissions than traditional diesel or octane when considering the fuel alone, but requires significantly more energy (and therefore carbon) to produce than fossil fuel per unit of fuel extracted. This is due both to farming energy use and the use of of fertilizers derived from fossil fuels. Large amounts of water are also needed to grow the corn.

In addition, the really widespread use of ethanol would require changes to the energy supply infrastructure that would also have a carbon cost. It would also set up a conflict between food and fuel production priorities. The use of hydrogen fuels may become feasible in future, but at present these are largely developed from fossil fuel, or carbon-containing sources.

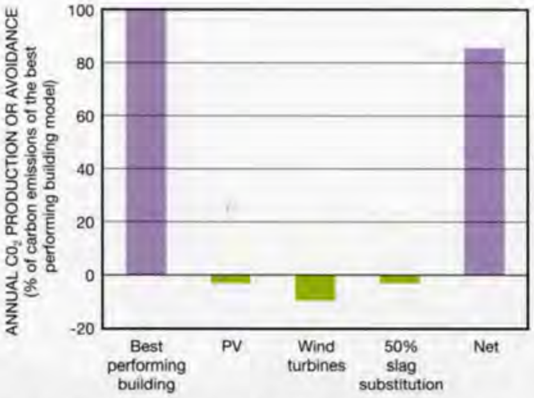
## Summary

To get to zero net energy or zero net carbon it is necessary to do many things. There is no single solution, and something has to be done at each of many levels. For buildings, at the smallest scale, occupants have to be trained to consider their expectations for thermal comfort. At a larger scale our buildings must be designed to use as little energy as possible and to harvest as much of their energy as possible on site. At the city or neighbourhood scale, building owners need to co-operate with their neighbours to share equipment and power, and at the national or regional scales it is necessary to move towards a regional renewable power infrastructure, bearing in mind the amount of embodied energy required to construct one.

For transportation, at the smallest scale, people need to plan their travel to minimize car use, and buildings and cities need to be planned to make this as easy as possible, whether this is through the provision of incentives to car-pool or cycle, through strong public transit networks, or through design for walkable communities or congestion charging.

Reducing carbon emissions will take efforts at all these scales and the commitment of individuals, corporations, cities, and states.

Finally, we shouldn't take our eye off the broader sustainability concerns. In the real world, the single-minded pursuit of "zero carbon", without regard for other consequences, is simply not practicable. While it may not have the dramatic ring of "zero carbon", a more realistic goal should be the least carbon output possible without producing disastrous consequences in terms of other resource systems, economic insecurity, maldistribution of wealth, or impacts on human health.




9. The effect of substituting 50% of slag, produced as a by-product of power generation, for concrete - amortized over the assumed 50-year lifetime of the building.

**Fiona Cousins** is a Principal of Arup in the New York office. She is a mechanical engineer and the leader of Arup's Americas Region sustainability skills network.

### Credits

**Illustrations:** 1 Graffizone/iStockphoto.com; 2 Jgroup/Dreamstime.com; 3 Robert Stava, Arup; 4-6, 8, 9 Arup/Nigel Whale; 7 NOAA/NGDC, DMSP Digital Archive; 8 US Department of Energy.

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1. Overall view, showing the in-run, connecting bridge, and tower with the cantilevered warm-up capsule at the top.

# Ski-jump, Klingenthal, Germany:

## Design, analysis, and construction

**Joachim Güsgen Eva Hinkers Torsten Wilde-Schröter**

**With minimal intrusion on the landscape, this bold, clear steel structure constitutes a new development in the design and construction of ski-jumps.**

### Introduction

The town of Klingenthal in Saxony's Vogtland region, near the border with the Czech Republic, is a well-known winter resort. Its training centre for competitive sports and the promotion of young talent was named an "Elite School for Sports" by the German Sports Association (DSB), and it is also home to the VSC, Saxony's biggest winter sports association. Vogtland District Council planned a modern ski-jumping facility in Klingenthal to meet the requirements of the international ski association (FIS), and it was designed by architects m2r, with Arup as structural engineer. The client's desire for a modern, safe, architecturally ambitious, but low-cost facility was met by the design and construction of this very light, almost filigree steel structure.

### Design and structural framework

The principal parts of the project are the ski jump tower, the warm-up capsule at the top, the connecting bridge, and the in-run (Fig 1).

### *The tower*

The 35m high tower provides vertical access to the ski-jump and has a lift installed at its side, as well as a cantilevered projecting staircase (Fig. 2). The tower is a square truss, with the four corner vertical chords connected by horizontal bars and diagonal tension members. The vertical chords and horizontal bars are made of circular hollow sections welded together (vertical chord: 406.4mm diameter with 12.5mm wall thickness; horizontal bar: 273mm diameter with 16mm wall thickness).

For simplicity of assembly, the tower was prefabricated in three sections and assembled on site. The stringers of the staircase are formed from 369mm x 100mm welded rectangular hollow sections (16mm wall thickness), which also extend around to become the frame for the circular platforms at each level.

The steps have grilled surfaces bearing on canted metal sheets, which are welded to the stair stringers.

3. The capsule (warm-up room) and connecting bridge between tower and in-run.

2 The tower with cantilevered staircase at the side.

### *The capsule (warm-up room)*

The capsule at the top of the tower is used as a warm-up and rest space during competition and training (Fig. 3). At other times it is open to the public as a viewing platform. It was built as an elliptical barrel, projecting approximately 10m towards the valley side. Four double T- beams, curved into the required elliptical shape, form the framework, and the capsule sits on two tapered, welded box girders which pass over the top of the tower and are restrained on the far side.

### *Connecting bridge*

The bridge links the in-run below to the top of the tower. On the other side a grout storage box is fitted. The bridge basically comprises two welded hollow girders connected by box-shaped transverse girders, and braced with diagonals made from circular hollow sections.

### *In-run*

The in-run is in two parts. Uppermost is a 55m long trussed girder, whilst the lower part is formed of 10m long, simply-supported, welded hollow beams linked by transverse hollow square sections and laid directly on the slope. A flexible joint connects the bridge to upper end of the trussed girder, supported by an inverted V-shaped trestle, and the girder's lower end bears onto a concrete abutment.

The truss is triangular, with two upper booms in welded box sections and tensile rods as lower tension booms, and has a maximum camber of about 3.5m. At the upper side of the girder, protruding 4.45m from the central axis, are stairs made of three longitudinal beams supported by cantilevers. Spanning between the longitudinal beams are grilles that form steps for the skiers as they prepare to jump.

## Foundations

The site generally comprises layers of backfill, brickearth and debris, with underlying weathered phylite. The nature of the top layers made it necessary to found the structure directly into the phylite on seven individual foundation elements.

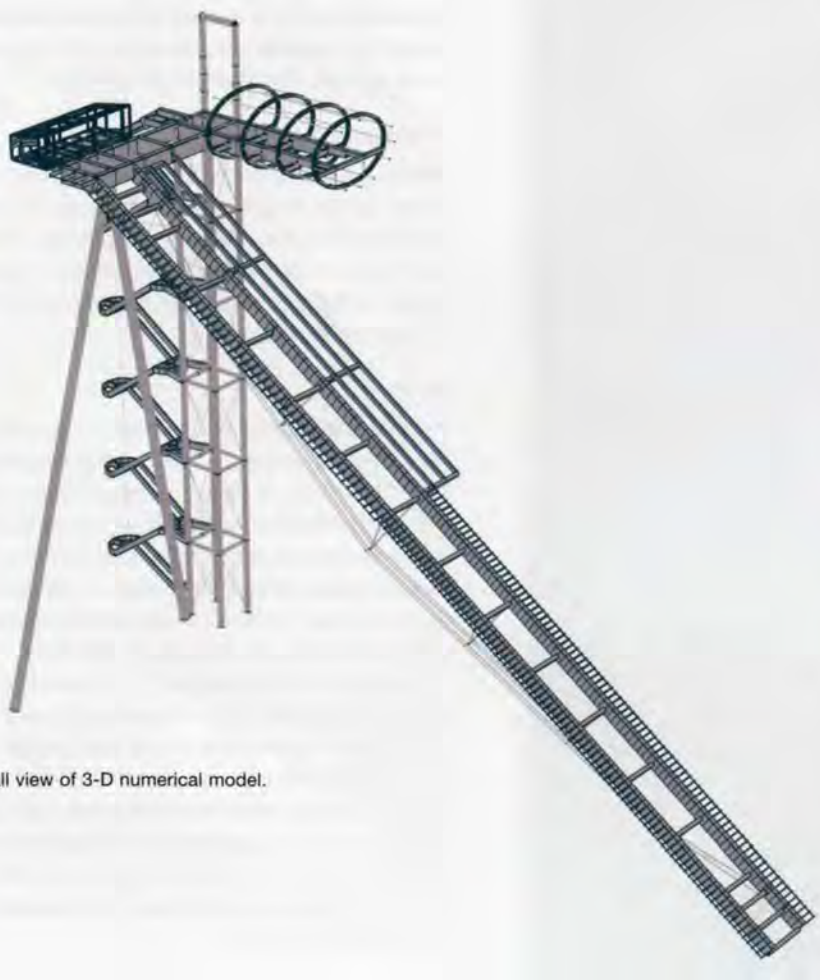
All the foundations are of reinforced concrete on bored piles, with the exception of the jumping platform. The position of the floor slab relative to the load-bearing subsoil made a locally restricted soil replacement the most cost-effective solution for this element.

The front wall of the jumping platform is founded above a tunnel that runs directly underneath. The foundation elements under the main support of the tower and the jumping platform not only function as foundations but also form storage and plantroom areas.

## Static calculation and design

### *Concept*

Because of its spatial complexity and expected large deformations, the ski-jump was analyzed as a 3-D framework model (Fig 4). Members subject to bending are represented as beams. Bracing elements in the tower, the in-run, and the capsule are represented as tensile bars. Arup's finite element GSA program was used. As well as assessing the stresses in the various elements, GSA was used to calculate the buckling eigenvalue, associated buckling shape, and second order effects. The dynamic response was also checked to ensure acceptable vibration levels for those using the jump.



4. Overall view of 3-D numerical model.

### *Design load*

The standard loads were specified according to *DIN1055*[1]. Klingenthal's relatively high snow loads had to be taken into account, as were additional ice loads 50mm thick on all sides, exceeding the standard estimate.

Wind loading in accordance with *DIN1055; Part 4* was evaluated. To allow for gusts, the wind load is multiplied by a dynamic factor equal to 1.2 (*DIN4131*[2]), with the approval of the proof engineer. For simultaneous wind and imposed load, the maximum wind load was combined with only 50% of the imposed load, since nobody would be on the jump at full wind force. This was accepted by the proof engineer.

According to *DIN4149*[3], seismic loads also had to be calculated since Klingenthal is in a seismic zone. The ski-jump is not easily classifiable within *DIN4149*'s three construction categories, but since this is a requirement for stability proofing, after consultation with the proof engineer it was placed in building category 2, which includes buildings that may accommodate numerous people, and are at greater seismic risk due to their structure. A horizontal acceleration of $0.21 m/s^2$ was considered.

The load condition temperature was taken into account by constantly changing the central temperature of all construction elements according to *DIN1072*. Thermal fluctuations of ±35°C around a construction temperature of +10°C were considered.

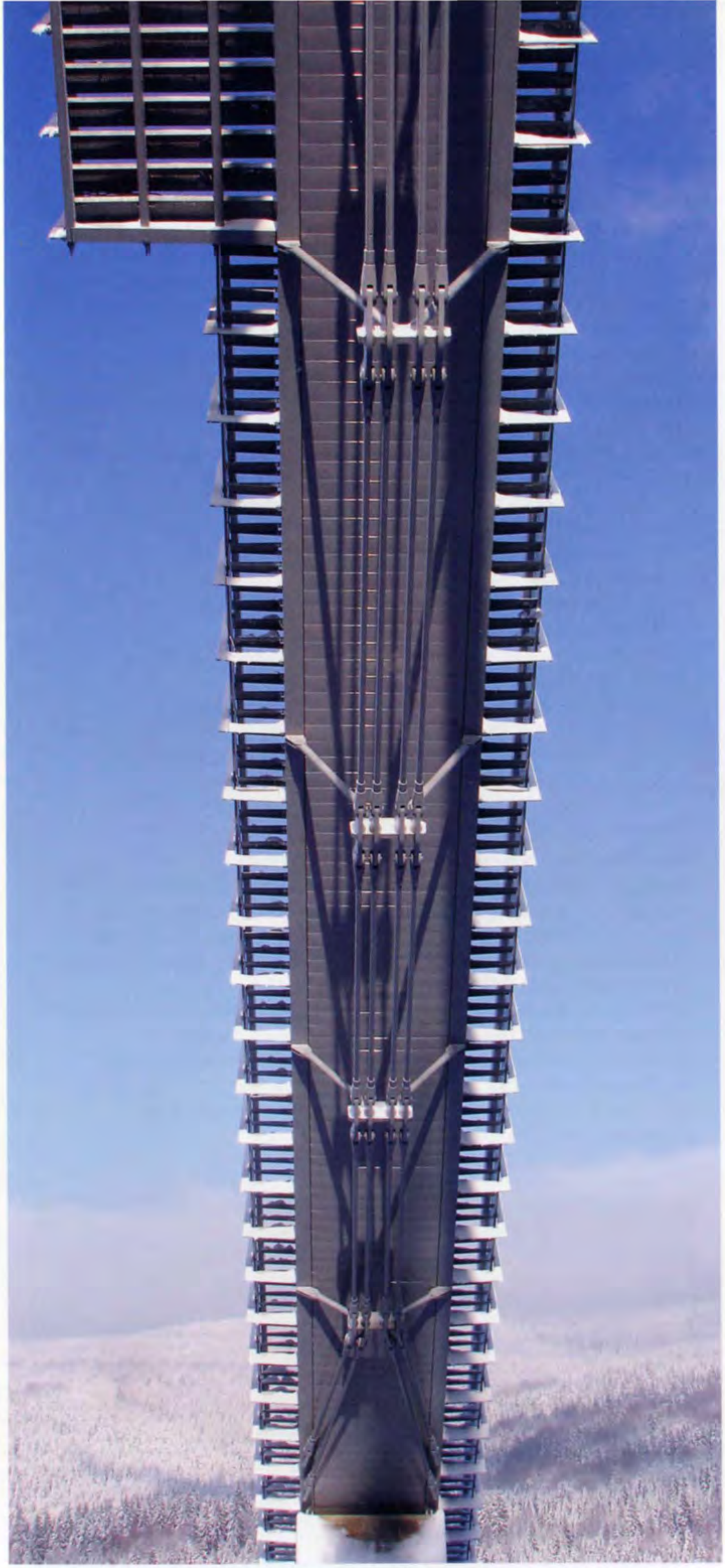
Load combinations are not calculated according to *DIN18800-1*[4] with a uniform load factor of 1.35 for several variable loads, but follow *DIN1055-100*[5] incorporating combination factors.

### *Imperfections*

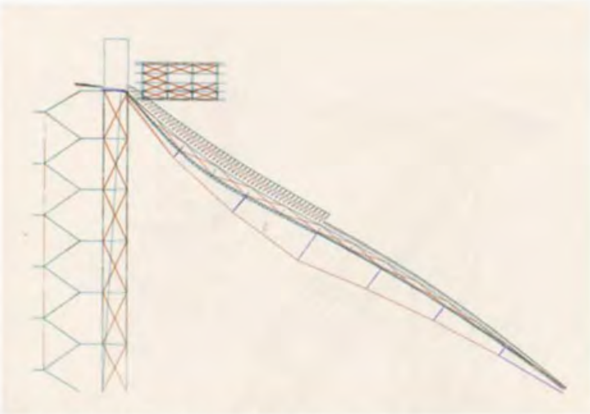
According to *DIN18800-2*[4] geometric and material imperfections must be considered if they increase stresses. To ascertain both types of imperfections, geometrical substitute imperfections can be used. These are estimated (*DIN18800-2*) to conform as much as possible to the deflection shape associated with the lowest buckling eigenvalue.

**Stability checks**

The edge members of the trussed girder and the corner vertical chords of the tower were considered particularly susceptible to buckling, and a criterion in *DIN18800-1* was used to determine whether second-order analyses were required. On applying this check to the vertical chords, it became evident that their stiffness in combination with the inverted V structural hollow section supports was sufficient for linear analyses to be used for their design.



5. The underside of the bridge, showing support structure.



6. Buckling shape from GSA analysis.

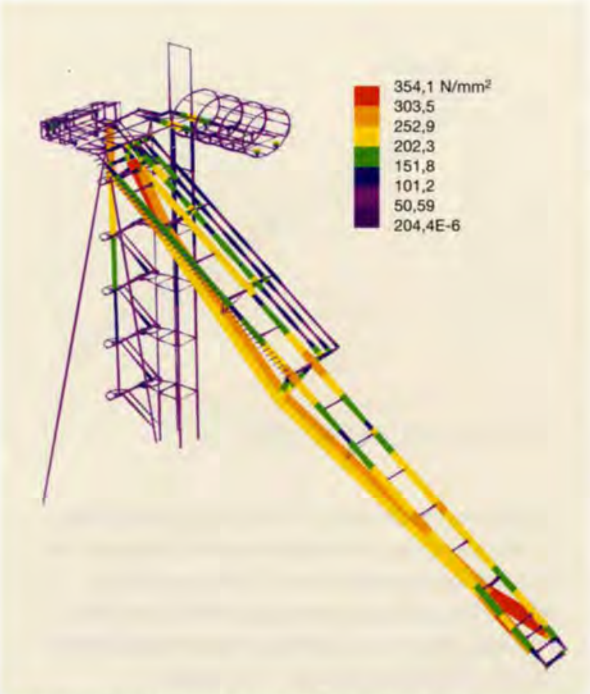
For the edge members of the trussed girder, GSA buckling analyses were performed to determine the most adverse combination of loads for stability (Fig 6). The critical combination comprised dead, imposed, snow, and ice loads, wind longitudinal to the in-run, and temperature. The modal displacements from the lowest mode are scaled so that the value $w_0$ of the imperfect shape accords with *DIN18800-2*. This imperfect shape is used for a subsequent second-order analysis.

### *Seismic calculation*

The lowest 10 dynamic modes were ascertained using GSA and then used in a response spectrum analysis according to *DIN4149: Part 1*. For safety, it has to be checked whether seismic loads effects exceed the linear effects of the permanent loads (without wind loads), and whether the resulting stresses comply with the *DIN4149: Part 1* permitted stresses. According to *DIN18800-1*, partial load factors of 1.0 may be used for extraordinary combinations. It became clear that seismic effects were not decisive for the ski jump design.

### *Design*

The forces and stresses in the elements were calculated for the specified load combinations using a second-order analysis, as described above. For all other load combinations which do not cause a risk of buckling, linear calculations were carried out. The forces and stresses from all these load combinations were then enveloped to give the critical stresses in individual elements in the tower, emergency stairs, capsule, bridge, trussed in-run girder, and in-run in the slope (Fig 7).




7. Forces and stresses in the 3-D numerical model.

Apart from the calculations of the construction elements, detailed calculations were made for the decisive joints and connections. These included the welded hollow section connections, designed according to Dutta[6] and CIDECT[7]. The lower and upper support points of the trussed in-run girder were constructed as stud connections, according to *DIN18800-1*. All further joints and connections also comply with *DIN18800-1*.

### *Serviceability*

Compliance with permitted deformations and with dynamic requirements confirmed the structure's serviceability. Since it is lightweight, with high useage demands during competitions, those involved in the planning (client, proof engineer, structural engineer) jointly agreed on the permitted deformations. After consulting the proof engineer, for the trussed beam exposed to permanent loads (own weight and finishes) the permitted deformation was determined to be l/500 (l = the span length of the beam).

The cantilever beams of the capsule are precambered by 100% of the calculated dead load deflection. The edge members of the in-run girder are precambered by varying degrees because of the eccentric load from the starter stairs. The edge girders are precambered by 90% of the calculated dead load deflection.

## Dynamics

### *Requirements*

A dynamic analysis was necessary to ensure the safety of people using the jump. Current German building standards contain no stipulation regarding vibrations, so the design team resorted to other literature both from Germany and beyond, as well as experience. The client and operator defined the requirements regarding the existing imposed load and the permitted wind load at operating times, and the dynamic analysis was based on these. Also, the following imposed loads were estimated: in-run (starting beam), one person sitting; start stairs, one person jumping; platform at stairhead to the start stairs, two persons jumping; warm-up room (capsule), 10 persons in total (four moving about).

The client confirmed that the maximum wind speed during jumps would be 2.3m/sec, so this was the basis for examining the dynamic effects of wind loading. The client and operator had no requirement to use the ski-jump outside these operating times.

The following checks for imposed and wind load were needed:

- ultimate limit state for maximum wind speed
- ultimate limit state at excitation of the entire structural framework by vortex vibrations and self-induced vibrations
- ultimate limit state for vortex shedding at structural elements
- assessment of structural safety for people movements
- serviceability limit state for wind load during operation of the jump
- serviceability limit state for vertical vibrations caused by people during jumps
- serviceability limit state for horizontal vibrations caused by people during jumps.

A damping coefficient following Petersen[8] of 0.007 was used.

### *Modal analysis*

To determine the effects of vertical and horizontal vibrations, the modal shapes, frequencies, and masses were taken from the GSA modal dynamic analyses; the mass for these analyses comprised the dead load of the steel construction and finishes. To estimate the vibration, four 3-D numerical models were generated: (1) the entire jump construction; (2) the trussed in-run girder; (3) the tower stairs; (4) the projecting capsule (Tables 1, 2).

The lowest vertical vibration frequencies for the trussed in-run girder and for the projecting capsule are below 3.5Hz. For these elements, the expected accelerations were calculated to estimate the effects on people on the jump. Similarly the lowest natural frequency of the horizontal vibrations amounted to about 1.4 Hz for the entire structure, which meant that these expected accelerations had to be calculated too.

Table 1. Vertical vibrations.

| Model | Specification | Natural frequency (Hz) | Modal mass (kg) |
|---|---|---|---|
| 2 | Trussed in-run girder | 1.484 | 30 430 |
| 3 | Tower stairs | 7.910 | 14 880 |
| 4 | Projecting capsule | 2.805 | 10 110 |

Table 2. Horizontal vibrations.

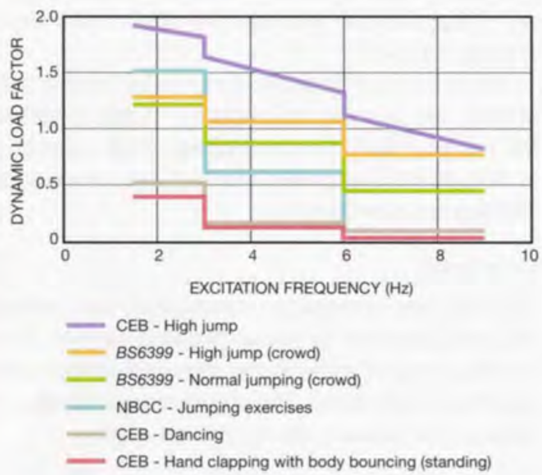
| Model | Specification | Natural frequency (Hz) | Modal mass (kg) |
|---|---|---|---|
| 1 | Complete construction, the in-run girder swerving to the side, and the tower turning | 1.366 | 40 420 |
| 3 | Tower stairs | 4.626 | 4623 |

8. Side view of bridge support structure.

The following acceleration limits were recommended for Klingenthal: warm-up room (people waiting) 3%g; in-run girder (still, focused ski-jumper) 0.9-1.2%g; tower stairs 5%g.

People are more susceptible to horizontal vibrations than to vertical ones. Based on data in *ISO2631-1*[13], the relative sensitivity within the problematic frequencies (1- 2Hz) is approximately 2:3. On this basis, 2%g, 0.5%g, and 3%g horizontal acceleration limits were respectively recommended for the warm-up room, the in-run girder, and the tower steps.

9. Data in reference sources for dynamic loading from jumping and dancing.




*Dynamic loads*

When a system is agitated by people, movements vary for floors, pedestrian bridges, and stairs, differing not only in frequency but also greatly in dynamic force. Walking, running, and jumping can generally be distinguished.

The most comprehensive research on the relationship between human movement and static and dynamic load has been carried out in Canada. The findings have been integrated into the National Building Code of Canada (NBCC)[9], which embodies 30 years of laboratory measurement of dynamic loads, and on-site analysis to test the data in real conditions. Fig. 9 compares NBCC data with other sources. In analyzing the ski jump, a dynamic load factor of 1.5 was calculated for vertical vibrations caused by humans, corresponding to the NBCC.

Human movement can also generate considerable horizontal forces, particularly in frequency range 0.5-1.5Hz (Table 3).

For vibrations in the direction of wind gusts, the dynamic effects from wind are taken into account with a gust factor of 1.2, according to *DIN4131*.

*Criteria for acceptance of vibrations*

The vibration level had to be comfortable for users for the structure to be accepted as serviceable, as structural vibration can easily affect well-being. People can tolerate minor accelerations over several hours, but greater accelerations, even for a short period, are bothersome or even a health risk. Table 4 lists some recommended quantities of acceleration for the acceptance of vertical vibrations, bearing in mind that even very low vibration levels are clearly perceptible, eg 0.1-0.2%g.

**Table 3. Dynamic load factors.**

| Direction of motion | Basic frequency (Hz) | Dynamic load factor (first three harmonics) | | |
|---|---|---|---|---|
| | | $\alpha_1$ | $\alpha_1$ | $\alpha_1$ |
| Left-right | 0.5 – 1.5 | 0.25 | 0.05 | 0.04 |
| Back-forth | 0.5 – 1.5 | 0.05 | 0.04 | 0.02 |

**Table 4. Acceptance of accelerations.**

| Source | Category | Acceleration limit |
|---|---|---|
| NBCC | Eating and dancing | 2%g |
| | Pop concert or sports event | 4-7%g |
| CEB[10] | Sports halls | 5-10%g |
| | Dance halls | 5-30%g |
| Kasperski[11] | Irritation (passive public) | 5%g |
| | Tolerance/discomfort (passive public) | 18%g |
| | Fear/panic | 35-70%g |
| Willford[12] | Shopping malls | 1-2%g |
| | Pedestrian bridges inside buildings, and staircases | 2-5%g |
| | Pedestrian bridges | 5-10%g |

*Results of calculation of dynamics*

Calculation of accelerations from people-induced vibrations during jumps, and comparison of these with the acceptable limits, showed that dampers might be required for the in-run and the projecting warm-up room, but experience in use showed them to be unnecessary. Accelerations caused by wind vibration do not affect the load-bearing capacity or serviceability of the construction.

**Execution and assembly (just-in-time-planning)**

The high degree of prefabrication possible with steel construction made building relatively simple on the not easily accessible site. The entire project, including façades, fittings and technical installations, was completed within four months.

The tower was transported to the site in three 10.5m sections, where they were erected by mobile crane and connected (Fig 10). The emergency staircase at the side of the tower was then added, and simultaneously construction of the cantilever in-run girder and setting up of the cantilever beams for the warm-up room were begun. The upper boom of the in-run - the two edge beams, transverse beams, and cross-bracings - was also delivered in three sections and erected on site with auxiliary supports.

The bridge and its supports had to be constructed before the last part of the in-run could be assembled. After the structural framework was constructed, the finishes, installations, and façade of the warm-up room were completed.

The structural engineers and contractor worked together very closely on joint detailing and checking.

**Conclusion**

This plain steel construction constitutes a new development in the construction of ski-jumps. Intrusion on the landscape is minimal, due to the structure's delicacy, and the choice of material also allowed a considerable degree of prefabrication, reducing on-site labour. The committed co-operation of all involved enabled the project to be realized with the desired quality.

10. Assembling the second section of the tower.


**Joachim Guesgen** is a senior engineer in Arup's Düsseldorf office, and was a structural designer of the Klingenthal ski-run.

**Eva Hinkers** is an Associate Director of Arup in the Düsseldorf office, and was Project Director of the Klingenthal ski-run.

**Torsten Wilde-Schröter** is an Associate of Arup in the Düsseldorf office, and was Project Manager of the Klingenthal ski-run.



**Credits**

**Client:** Vogtlandkreis, Amt für Kreisbauten **Architect:** m2r-architecture **Structural engineer:** Arup – Joachim Guesgen, Volker Hass, Eva Hinkers, Patrick Lürmann, Torsten Wilde-Schröter, Peter Young **General planning:** Greiner Ingenieure GmbH/Schunk Bauprojekt **Proof engineer:** Dr-Ing Beierlein **Main contractor:** Stahl- und Glasbau Schädlich GmbH **Concrete contractor:** VOBA **Illustrations:** 1, 2, 3, 10 SCHUNK Bauprojekt; 5, 8 m2r-architecture; 4, 6, 7 Arup; 9 Nigel Whale.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# Demographics as a driver of change

Francesca Birks

### Introduction

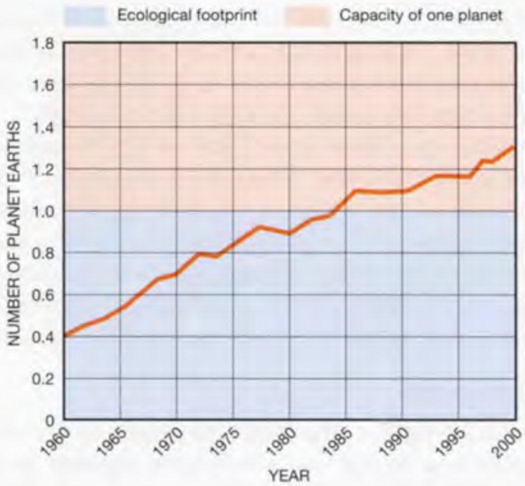
UC Berkeley demographer Ronald Lee defines demography as "the study of the causes and consequences of demographic rates and structures, where demography rates are fertility, mortality, nuptiality and migration, and structures include size and distribution by age, sex, race-ethnicity, and geographic location"[1].

Humans are influenced by, and can also influence, what Arup's Foresight + Innovation + Incubation group has dubbed the "Drivers of Change"[2]. Previous *Arup Journal* articles[3-5] have examined energy, climate change, and water, and shown how complex and interconnected these drivers are.

The same is true for demographics, as demographic change often results from a combination of interlinked economic, political, social, technological, and environmental factors. The nature of the linkages is sometimes difficult to unravel; easier to discern is the fact that evolving population patterns will affect change in the global environment, and that, in turn, changes in economic and political systems will influence population dynamics. While forecasts of future populations may be filled with degrees of uncertainty, it becomes no less important to try to understand demographic projections and their potential impact on human society, as well as on organizations like Arup.

Population growth without proper management, and fuelled by a perceived need for economic growth, is extremely problematic for our planet because it drives resource consumption. Since 1985 we have surpassed the Earth's capacity[6] and at present humanity's ecological footprint is 23% greater (Fig 2) than its estimated sustainable level[6]. Evidence of the pressure we are putting on the Earth can be found everywhere. The UN has predicted[7] that as many as 50M people could be considered environmental refugees as soon as 2010 due to deforestation, rising sea-levels, expanding deserts, and catastrophic weather events (Fig 3).

Many environmental disasters are concentrated in developing regions of the world where their systems are more acutely vulnerable to the effects of climate devastation than neighbours in developed regions. Environment-related migration has been most acute in sub-Saharan Africa, but also affects millions of people in Asia and India. The Red Cross has stated[7] that environmental disasters already displace more people than war, and they show no signs of slowing down.




2. Humanity's ecological footprint[6].

**What will the populations of the future look like? Is it even possible to predict? Though uncertainty is inherent in future population projections, this makes them no less important to try and understand.**

## World population projections

Before we discuss population growth, the way population projections are made must be considered. Generally the population of a geographic area is established through three fundamental variables interacting: fertility, mortality, and migration.

To project the future size of a population, demographers make assumptions about levels of fertility and mortality, and estimations of how many people will move in and out of an area during the projection period. The net increase or decrease over that period (numbers of births and in-migrants minus the numbers of deaths and out-migrants) is added to the baseline population to project future population size. Demographers often prefer not to make projections more than a few decades into the future, when most of the population will be "unborn", but global change researchers are increasingly asking for longer-term projections. Their interest is generated by concern about the potential impact of demographic drivers, including ageing populations, which affect social and economic security systems worldwide.

There is also concern about the effects of reduced fertility and declining populations on economic growth in developed regions, and the implications of demographic trends on the long-term wellbeing of the environment. Global projections have generally been the work of only a few institutions, such as the United Nations, the World Bank, the US Census Bureau, and the International Institute for Applied Systems Analysis[9]. While forecasts of future population dynamics are uncertain, this does not make population projections any less important, and newer methodologies are being developed to improve accuracy and make their results easier to understand by a wider audience.

## Population growth: two realities

According to UN forecasts[10], world population is expected to stabilize at about 9bn by 2050. Currently India is home to 17% of the population and in three decades' time, on current projection trends, it is expected to surpass China as the world's most populous nation*. By 2050 Asian countries will head the top 10 in terms of projected population growth, with the USA the only Western country remaining in the top 10. According to the US Census Bureau, it will acquire 80% of its additional population from developing regions' immigrants. Africa's share of world population will increase, but Europe's will shrink from 20% to about 7% by the next century. Almost all the increase will be in less-developed countries, and here a disproportionate share of the increase will be among the poorest poor and in urban areas often lacking the infrastructure to support the population growth.

## Urbanization

While the topic of urbanization *per se* as a driver of change will be addressed in a future *Arup Journal*, the trend of urban migration should also be discussed within the present context. Over the next three decades the population of urban areas in less-developed regions is expected to increase and even double in size - from 2bn to 4bn by 2030[12] (Fig 4). In 1950 one-third of the world's population lived in cities; it is projected that 100 years later nearly two-thirds (6bn) will inhabit urban areas.

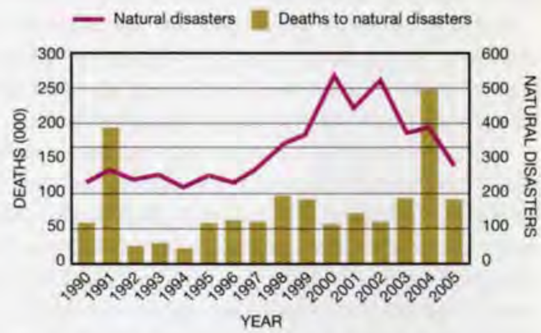
China is seeing a great movement of its population from the rural interior to cities in the east. In 1950 the urban population represented less than 13% of the total – it is now about 40% and it is expected to reach 60% by 2030[13]. It remains to be seen whether China will successfully manage moving 300M farmers from the countryside to urban areas in just 20 years. If current tensions between the farmers and the state are any indication, it is going to be a slow and tortuous transition. Other countries facing similar patterns of transition should take note.

*According to the US Census Bureau's IDB population pyramid projections[11] for 2025, China has an ageing profile, whereas India's population pyramid remains relatively youthful.
**Where already 900M people live.

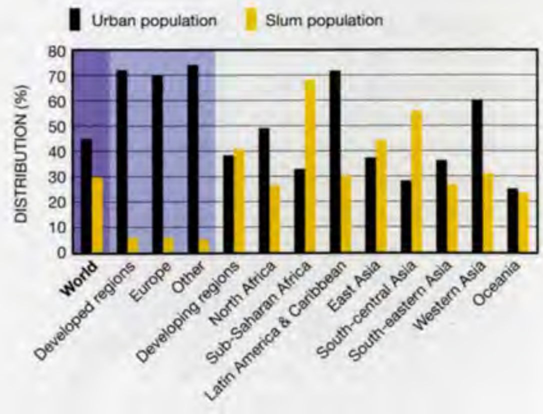
Most of the world's population growth is in the urban areas of the less-developed regions where 85% of the total world population lives. In sub-Saharan Africa the population is increasing by more than 5% per year[14]. Much of the urban growth is mirrored by the expansion of informal settlements**, characterized by insecure tenure, inadequate housing, and lack of access to water or sanitation. UN-HABITAT figures for 2004[15] show that a quarter of the world's urban population does not have adequate housing.

If the expected population growth continues in the years to come, there is little doubt how the situation will develop in relation to these informal settlements, with capacity constraints becoming increasingly severe in areas that already lack proper access to water and sanitation. To what extent will Arup's future business be involved with the development of these challenged areas?

As the population of the world rises and global consumption rates soar, with energy supplies rapidly disappearing and climate change eradicating valuable farmland, the conclusion is inescapable that the stage is becoming set for worldwide struggles over resources. Everyone needs water, food, and energy to survive, and with constraints in all three of these areas, the challenges could hardly be more serious.




3. Lives lost to, and numbers of, natural disasters[8].




4. Total, urban, and estimated slum population[14].

## Demographic transition theory

In the past two centuries, societies in developed countries are believed[10] to have undergone demographic transition - a shift from small, slowly growing populations with high mortality and high fertility, to larger, slowly growing populations with low mortality and low fertility. During demographic transition, population growth accelerates because a general decline in deathrate precedes that of birthrate, creating a sudden, but temporary, surplus of births over deaths. Data from all over the world support the relevance of demographic transition to today's less-developed countries. The transition is assumed to be advanced in all less-developed countries except sub-Saharan Africa, where fertility decline is just beginning to become apparent. Fertility is well below the replacement level of 2.1 in several less-developed countries such as China, Taiwan, and South Korea, and in countries in Latin America and south-east Asia fertility levels have fallen to those in developed countries just a few decades earlier[16].

The biggest difference between the transition in developed and less-developed countries has been the rates of mortality and fertility decline. In some OECD countries, mortality fell slowly for two centuries as food supplies stabilized and housing, sanitation, and healthcare improved. In many less-developed countries, mortality fell over just a few decades after World War 2 as medical, public health, and technological advances spread more quickly. Populations in less-developed countries are also growing more quickly than they did in developed countries at a similar stage of the demographic transition, although eventually their fertility levels are expected to decline to near replacement levels. The total fertility rate of the less-developed countries is twice as high as that of the developed countries, but nonetheless it is falling - between 1985 and 1998 TFRs (total fertility rates) in the less-developed countries dropped almost 40%, from 4.7 to 3.2.

5.

## Decline in total fertility rates

The gradual TFR decline has caused much concern and speculation among policy-makers in developed countries, which have both lower birth rates and extended life expectancy amongst their older populations. This has led to the development of policies to attempt to reverse the decline. In countries like Germany, which is experiencing some of the lowest fertility levels in the EU, governments have tried financial incentives to persuade women to have more children, but there is doubt as to whether such methods are the most effective means to reverse the decline. German Chancellor Angela Merkel's coalition government has gone so far as to promise to push Germany's dwindling birth rate to the top of the political agenda. A new form of state-funded child welfare support has been introduced by the Federal Minister for Family Affairs, whereby either the mother or father is entitled to 67% of previous income while staying at home, up to a maximum of €1800/month for 10 months. In Poland, parliament has passed legislation to pay women for each new child that they have. Under this plan each woman receives a one-off payment of 258 per child. Until recently Spain had strong public opposition to any form of government policy aimed at increasing fertility, as family planning was considered a private matter, but in 2003 the government introduced a national family policy. Norway has been more successful, managing a near-replacement level of fertility, partly because paid maternity leave is guaranteed by the National Insurance Act and dates back to 1956. The leave is financed through taxes so employers don't lose out financially when parents take leave. However, while European governments continue to tackle low birthrates with policies designed to balance work life with family life, no-one is quite certain about the consequences and implications for the developed world of its declining birth rate combined with ageing population[17].

## Why is fertility declining?

Early attempts to explain demographic transition pointed to industrialization and urbanization as the main drivers of change[9]. Economic modernization would lead to improvements in health and nutrition that decrease mortality, as well as drive changes in economic and social conditions that would make children costlier to raise, and thus reduce the size of families, eventually leading to lower fertility. The idea that reduced demand for children drives fertility decline gained popularity in the 1960s when the economist Gary Becker and others posited a microeconomic model[9] that described the choices parents are assumed to make between number of children and consumption of material goods. The model assumed that fertility falls because, as economic development proceeds, parents' preferences shift to higher quality expectations for themselves and their children, requiring greater investments in education and health. Alongside this, women's increased participation in the labour force and in wage-earning increases the opportunity costs of raising children. At the same time, development leads to a decline in some of the economic benefits parents used to derive from having children, such as household labour, income, and old-age security.

In the 1970s, the economist Richard Easterlin[9] added economic development to the environmental and cultural factors that might affect "natural" fertility (fertility in the absence of regulation) and to the costs (including psychological and social as well as monetary) of fertility regulation. Economic development might influence a woman's ability to bear children. In the 1980s, researchers continued to try to identify which social and economic factors were the most important causes of fertility change. Some explanations gave more weight to sociological than economic factors, while others argued for economics, stating that as children in post-transition societies displace parents as the main family beneficiaries, fertility falls.

While there is no precise consensus, clearly the fertility decline is caused by both economic and social changes, and by the spread of new ideas and cultural attitudes towards both birth control and children. Even some religious groups have changed their attitudes towards contraception. Acceptance of contraception by Christians only developed at the start of the 20th century, and some, notably Roman Catholics, continue to support only "natural" forms of birth control[18].

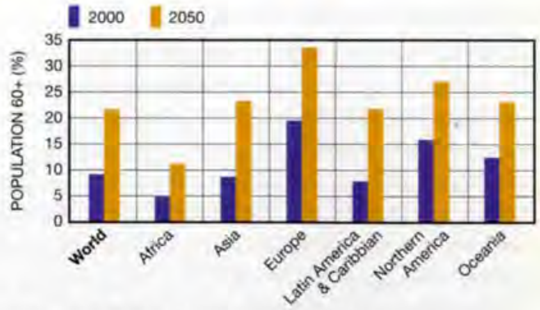
Demographers Susan Watkins and John Bongaarts have shown[9] that the diffusion of ideas and information about limiting fertility has had significant social impact. They demonstrated that fertility transitions typically start in leader countries where development levels are high and then spread to other countries in the region that have not yet reached the same level of development. Father and son Laurie and Matthew Taylor go even further and attribute[16] the demographic shift and decline to a dramatic change in our views of the value of children. They propose a growth in popularity of individualism and independence as traits in developed economies, and go on to suggest that the modern values of autonomy, freedom, and individualism are at odds with the sense of self-sacrifice that modern couples perceive to accompany child-rearing.

While some higher-income countries like New Zealand and the US continue to see replacement levels of fertility, their rates are almost entirely due to the respective Maori and Hispanic immigrant and minority communities. Even these rates show some signs of levelling off[16], indicating that fertility rates of immigrant and minority groups tend over time to match the average of the host country. Some may believe that a general ageing of the population will mean rising populations in most developed countries for several years to come. But what happens when an ageing population is matched with declining fertility levels, as in Japan? At current reproduction rates, Japan will soon be losing 500 000 inhabitants per year until 2050, when one in three Japanese will be 60. Recently Japan became the first country in history to have more 70-year-olds than 10-year-olds, and it is not alone in the ageing crisis. Given the current fertility rates in developed countries, and the expected decline of total fertility rates in less-developed countries, many - aside from India and the US - can expect to see a general greying of their populations. It is, however, important to note that fertility remains one of the most difficult rates for demographers to predict, as they cannot anticipate the shifting desires of women in low-fertility societies. Despite many plausible explanations, so far there has not been a theory that can predict female behaviour in low-fertility societies.

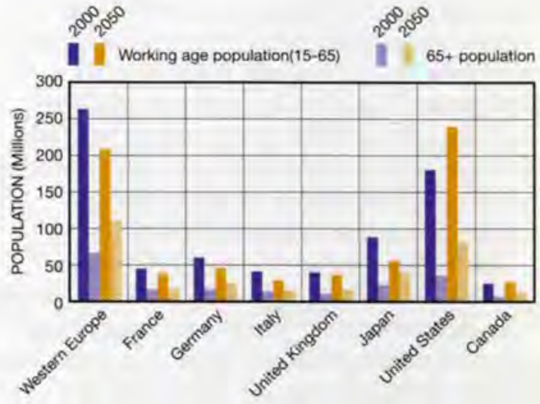
### Ageing populations

Population ageing results from reduced total fertility rates and/or an increase in life expectancy. This is characterized by increases in the proportion of oldest people and in the average and median ages, as we are seeing in developed countries. The elderly population is growing considerably faster than the world's total population - the number of older persons has tripled over the last half-century and will more than triple again in the next. Projections by the UN[20] show that by 2030 at least half the Western population will be over 50, with a life expectancy for 50-year-olds of a further 40 years, and that by 2050 the share of 65+ in the EU will hover at around 28% (Fig 6).*

Although the ageing phenomenon now particularly affects developed countries, it will also become a major concern for developing countries in the second half of the 21st century. By 2040, assuming current demographic trends, there will be 397M Chinese elders (60+) - more than the total current population of France, Germany, Italy, Japan, and the UK combined. In 2004, China's elderly made up just 11% of its population, but by 2040 the UN projects[21] that they will increase to 28%, a larger proportion than it projects for the US. Though Indonesia and Mexico, for example, will continue to have more youthful profiles in 2025 than the US of 2003, countries like Turkey and Brazil will be roughly as grey as the US of today,




6. Increase in age 60 and over by region[20].




7. Changes in working age populations[23].

but not as grey as today's Japan or Western Europe. Even Africa will be affected, and in a continent already facing shortages of resources and medical staff, the increased pressure of a larger elderly population will quickly make itself felt.

### What will this mean for the workplace?

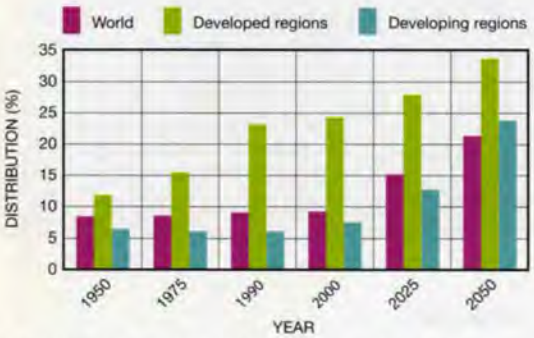
Three-quarters of 1400 global companies questioned by Deloitte in 2005[22] expected a shortage of salaried staff over the next three to five years (Fig 7). Japan anticipates its workforce shrinking by 16% (some 10M people) over the next 25 years. As a result of the expected boom in the ageing workforce, corporate pension schemes and health benefits are getting less and less generous. General Motors has revised its healthcare plan and will cap healthcare spending by its retired workers, and this is unlikely to be the last cut.

Old age dependency ratios will rise in every major world region during the next 25 years due to ageing populations. The world as a whole will face an elderly support burden nearly 50% larger in 2025 than it did in 1998 (Fig 8). In the US and other developed countries, elderly dependents will outnumber dependents under the age of 15 over the next 25 years. The total dependency ratio is projected to rise sharply over the next 50 years,

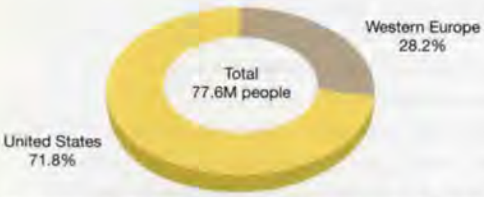
* In the UK, the old age dependency ratio - the number of older people aged over 65 who depend on those of working age between 16-64 - increased from around 20% in the 1960s to around 27% in 2003, and is projected to rise to around 47% by 2051.

due to the combined factors of low fertility rates and ageing populations.

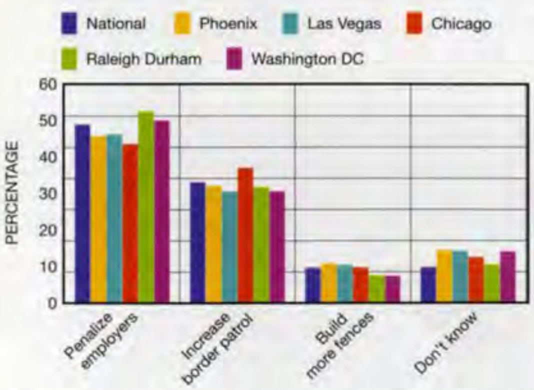
Both companies and individuals will need to re-evaluate perceptions of ageing and expectations of an ageing workforce. Because we know there will not be enough young people coming into the workforce, older workers will become more essential to employers. Flexibility on the part of employers will become increasingly important as baby boomers opt to swing between work and leisure modes. Merrill Lynch believes[25] that baby-boomers will reinvent retirement, cycling between periods of leisure and work well beyond the age of 65. Migration will also become increasingly essential for developed countries that lack the replacement levels of fertility to expand or maintain their labour forces, and for developing countries that see their skilled labour head to developed countries for better economic opportunities.




8. Proportion of people aged 60 and over, 1950-2050[24].




9. The "magnet effect": net number of immigrants, US and Europe combined, 2000-2050[23].




10. Views on the "best ways" to remove illegal immigrants to the USA from Mexico[26].

### Migration: why and where are people moving?

Migration has hit record levels, rising from an estimated 75M in 1960 to 175M in 2000. Migrants make up 3% of the world population, 30M more than 10 years ago. In developed countries one in 10 people is a migrant; in developing countries one in 70. Between 1960 and 2000 the number of international migrants in Australia, Japan, New Zealand, Europe, North America, and the successor states of the former Soviet Union increased by 78M, while the number in less-developed regions rose by 27M. Given that 2.8bn people live on less than US$2 a day, and 1.3bn have no access to clean water, it is easy to see why people are driven to move.

Migrants often travel for better work opportunities. In China they head from the countryside to urban centres for employment but generally get menial jobs, miss out on subsidized health care, and are often denied access to oversubscribed urban schools. The push factors for migration include a shortage of land, unemployment, famine, natural disasters, a lack of education, and overall poverty.

International migration is expected to continue to increase, with resource wars, environmental disasters, and food emergencies likely to make the push even stronger. On the receiving end, many developed countries will only experience population growth or population stability because of incoming waves of migration. 60% of the world's migrants reside in developed regions and 40% in the less-developed regions (Fig 9). The US is a perfect example of this scenario; currently it absorbs most of the world's international migrants; the propensity of Mexicans to migrate to US jobs more than doubled between 1990 and 2002. By 2050 the US is expected to be the only Western country among the top 10 for projected population growth, and according to the US Census Bureau, it will acquire 80% of its additional population from developing regions' immigrants. By 2016 minorities will make up one-third of the US population. Now one in seven, Hispanics will be one in four by 2016. Almost half (46%) of US population growth in the next decade will come from three states: California, Texas, and Florida, which will overtake New York as the third largest in the country.

### Challenges to migration

This raises the question of whether migration alone can fix declining fertility and labour gaps. Italy would need to increase its current immigration numbers from 80 000 a year to 400 000 a year. In fact, to maintain present population levels, Italy would have to absorb at least 2M immigrants every five years indefinitely into the future. A similar scenario is playing out in Germany. By 2020 the country will have to import 1M immigrants of working age each year to maintain its workforce. But what happens when these immigrants grow old? Is it not just delaying the inevitable? Governments would need to continue to import immigrants indefinitely into the future to maintain a consistent labour force to support its ageing populations and to keep its dependency ratio levels down.

Then there are the political and racial tensions around any large recruitment of external communities. Immigration is a hotly debated issue across the globe. Americans increasingly express concern, a growing number believing that immigrants are a burden to the country, taking jobs and housing and creating strains on the healthcare system (Fig 10). And the US is not alone in its debate. Certain parties across Europe are using the fertility deficit as a defence against any increase in immigration. In a 2000 regional election in North Rhine-Westphalia, Germany's most populous state, conservative contender Jürgen Rüttgers campaigned under the slogan "Kinder statt Inder" ("children instead of Indians") in response to the proposed 2000 plan of granting 20 000 time-limited residence and work permits to computer specialists from non-European countries - which among others included India. Austria's right-wing populist leader Jörg Haider has also played upon his country's fears that the eastward expansion of the EU will result in lost jobs. Given the presence of strong anti-foreign sentiment among European right-wing groups, any large increases in immigration seem rife with controversy.

## What can we expect of future populations?

**Because population projections of the future are based on assumptions drawn from past trends and current theories, they are quite uncertain and historically biased. Nonetheless, despite the uncertainty associated with any form of projection, it is still important for us to try and derive forecasts of future population dynamic if we want to influence its outcomes. Frameworks like the STEEP model can allow for a closer examination of some of the key issues and potential implications:**

### Social

Fertility will continue to decline even in countries which have had TFRs twice the norm of countries that have already gone through the demographic transition. However it remains difficult to predict TFRs in low-fertility countries. In dual household incomes the challenge to maintain balance between the public and the private spheres (work life vs family life) has to some extent led to the downscaling, or devaluation, of families. Governments have tried to put policies in place in developed economies to encourage fertility, but these have met with mixed success, indicating that policies alone cannot reverse the low-fertility trend. Companies that want to draw on the female labour pool may also have to look at their own policies to determine whether they are inadvertently creating roadblocks.

### Technological

Advances in biomedical research are extending and enhancing human life, but they carry ethical and moral dilemmas, and it remains to be seen whether these applications of science and technology will be lauded or demonized for their superhuman promises. And to what extent is this simply a dilemma for the developed economies? Will access to technology lead to a steeper wealth gap manifested in those who can afford bio-enhancements versus those who cannot?

### Economic

An ageing population will have economic consequences on societies with high dependency ratios, ie more retired than working-age citizens. In Europe, where one in five will be more than 65 years old within a couple of decades, it is anticipated that the absolute level of savings will drop across most of the continent. What is being done to address a situation in which growing numbers of potential beneficiaries of health and pension funds (mainly those 65 and over) are being supported by dwindling numbers of potential contributors? Unless the economic impact of this social reality is tackled, a decline in economic growth and living standards will follow. Retirement policies and pension plans are one area where companies can have an impact. One study[19] on behavioural economics shows that savings increase dramatically when a company automatically enrolls its employees in a voluntary savings plan. Now translate this issue to economically depressed areas like sub-Saharan Africa and we have a serious challenge on our hands. By 2020 there will be 1bn (1000M) elderly, and 70% of them in developing countries[27]. How can developed economies assist?

### Environmental

Desertification, rising sea levels, and extreme weather events are manifestations of climate change. The anthropogenic effects of our human activities on the environment cannot be overstressed[4]. Both the Living Planet Index[6] (the measure of overall trends in populations of wild species around the world), and the Ecological Footprint[6] (the measure of our resource use versus resource availability), confirm that our consumption patterns are not sustainable as far as the environment is concerned. When will our need for growth be surpassed by our need to preserve irreplaceable ecosystems? Humanity is having a harmful effect on the planet, which in turn is reacting and putting populations at risk. And while no one is safe from the devastation of climate change, people in developing economies are certainly more at risk, and we should see the environment-related migration patterns in Africa and Asia as proof of its life-changing consequences. Can we put measures and operational standards in place to try to ensure that our structures, and more generally our activities, are not contributing to environmental damage?

### Political

Some experts have related patterns of severity of the AIDS epidemic to regional poverty, and it is not difficult to see the relationship. Poverty pushes many men to become migrant workers; this disrupts family patterns, with the consequence of the men having multiple sex partners. Poverty also leads many women to become commercial sex workers, dramatically increasing their risk of infection. Cultural norms in these regions also usually make contraceptive decision-making a male prerogative, further putting women at risk. And health systems are not well-equipped for prevention, diagnosis and treatment. HIV/AIDS is having severe social and economic consequences for Africa, decimating its skilled workforce and leaving both a labour gap and an orphaned population that will have serious consequences for the imminent future. And Africa is not alone. In the decades ahead, the focus of global HIV/AIDS is expected to shift to Eurasia, which is home to most of the world's population; five out of every eight people on the planet live there.

Global migration patterns hit unprecedented record levels in 2000 and show no signs of letting up. People will go to great lengths to migrate for better economic opportunities publicized in their media; walls are no substitute for equality. How we choose to respond to migration flows is as much about policy as it is about the infrastructure that we put into place to navigate those interactions.

However, contrary to some of these immigration fears, a report by the Pew Hispanic Center[26] found that rapid growth in the foreign-born population at the US state level is not associated with negative effects on the employment of native-born workers. The report found that between 1990 and 2000 the top 10 states for foreign-born populations showed significant variation in employment outcomes for native-born workers. In five states native workers had employment outcomes that were better than average, whereas in the other five states they were worse than average. Subsequently this pattern remained consistent to 2004. Interestingly, assessments also showed that the size of the foreign-born population is unrelated to the employment prospects for native-born workers.

And what happens when former immigration pools decide to stay home because of better opportunities? Regions like Silicon Valley in the US used to recruit up to 25% of its talent pool from abroad, but it is currently facing recruitment challenges as graduates from universities like the Indian Institute of Technology decide to stay home because of greater opportunities and job security. Talented US graduates are expected to head overseas as well, because the job opportunities for business and information technology graduates are so plentiful. In this scenario competition for highly skilled talent is likely to become fierce.

## Conclusion

Ultimately, what we decide to do as individuals, and the way leading companies like Arup respond to the challenges of demographic change, are influenced by what we observe happening around us. Beyond our local spheres, articles like this and the new Demographics card set[28] in the "Drivers of Change" series are attempts to raise just some of the issues that need to be considered in our work. Everything that is built influences the lives within, and the communities and wider environment around. Greater awareness of demographics will almost certainly affect to what extent a built environment can be made sustainable for all communities.

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**Credits**

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To celebrate its 60th anniversary in 2006, Arup partnered with the international charity WaterAid in the Arup Cause initiative, which focused Arup's mission to "shape a better world" on the provision of safe domestic water, sanitation, and hygiene education to the world's poorest people.

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Front cover: The cantilevered warm-up capsule at the top of the ski-jump at Klingenthal, Saxony, Germany (Photo: Arup/m2r-architecture).

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