The Pavilion, Regent's Place

The Pavilion marks the new western entrance into Regent's Place, a 13-acre development in the heart of London which features retail, leisure and public spaces. It is a structure made entirely of stainless steel in which a field of vertical columns supports a roof canopy 8 m above street level. The pavilion is 20 m by 5 m in plan, with 258 highly slender rectangular hollow sections supporting a roof plane, reflecting sunlight during the day and projecting light at night from lights integrated into the paving. The structure was opened to the public in 2009 and won a 2010 Royal Institute of British Architects (RIBA) Award for architectural excellence.

Material Selection

A design life of 50 years was specified for this structure. Initially carbon steel with a painted or galvanised finish was considered, but stainless steel was preferred because it provided superior durability coupled with an attractive appearance.

Duplex stainless steel grade 1.4362 (S32304) was initially chosen for the entire structure. This is a grade which combines high strength (about 450 N/mm^2) with excellent corrosion resistance. However, the combination of small section dimensions and relatively thick wall meant this grade could not be sourced in the required section sizes. Austenitic grades were then considered and finally grade 1.4404 (S31603) was chosen. This grade has similar corrosion resistance to 1.4362 in atmospheric exposure but a lower strength (about 220 N/mm^2). This lower strength led to a 15 % increase in the overall weight of the structure.

In order to specify the required surface finish for the columns and roof, lighting tests on a 1:1 mock-up were carried out; the selected finish was a 320 grit polish. The finish was applied at the mill which meant no third party specialist finishing operations were required, thus saving costs.

Figure 1: The Pavilion, Regent's Place, illuminated

Design

The pavilion is entirely made of stainless steel and comprises 258 columns that are linked together by a 3 mm thick stiff roof plane. The columns are 7.8 m long but only 50 mm square with 4 mm wall thickness. The structural integrity of the columns is governed by the pavilion's global buckling performance. The columns have been arranged so they shelter each other from prevailing winds. This reduces the overall wind load and allows lighter loaded columns to provide greater overall global resistance to buckling failure.

The unusually high column slenderness was only possible by a design approach developed from first principles which involved establishing project-specific loading, deflection and acceleration criteria.

Structural Analysis

Direct wind pressure and drag imposed on the columns is transferred to the roof plane and distributed to all elements which act together as a sway frame. The structure is sway-sensitive (low critical load factor) and was therefore subjected to a non-linear P-Δ analysis. Forces from this analysis were then combined with those associated with the primary buckling modes such that the section capacities are not exceeded.

Unlike carbon steel, stainless steel exhibits non-linear stress-strain characteristics with no clearly defined yield point. This reduction in stiffness as the stress approaches the design strength (0.2 % proof strength) is known to amplify forces associated with geometric non-linearity and was considered explicitly in the design.

Physical tests described below showed that the level of intrinsic damping was very low (circa 0.2 % of critical). Dampers were developed to control the structure’s dynamic response so that its fatigue life (calculated to BS 7608 [1]) exceeds the 50 year design life.

An independent academic reviewed the calculations produced by the designer and assessed the likely structural performance against the design recommendations in EN 1993-1-4 [2].

Wind Response and Damping

From an early stage, aeroelastic instability of the individual columns was a primary concern and wind tunnel tests were commissioned to investigate the response of the columns. These tests studied excitation from galloping, vortex shedding and interaction vortex shedding. It was found that, in the absence of supplementary damping, the columns would start to gallop and resonate at a wind velocity of 8 m/s. (This is an aeroelastic effect similar to that which caused the failure of the Tacoma Narrows Bridge in 1940.) Since this is a credible wind speed for the site, further tests were carried out to determine the amount of supplementary damping needed to confine the resonant response to wind speeds that exceed those ever likely to occur at the site. It was discovered that introducing 2 % of supplementary damping would increase the critical wind speed to 80 m/s.

Impact dampers were proposed that would take the form of carbon steel rods coated in plastic and hung inside every column. As the columns start to vibrate, the bar collides with the inside face of the column and in so doing absorbs sufficient energy to control the response of the column.

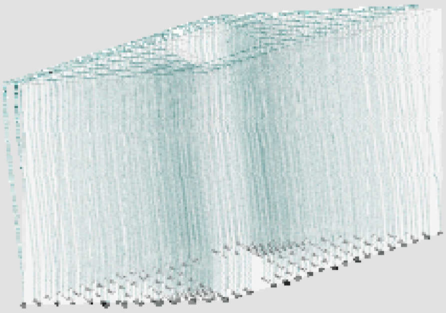

Figure 2: Modal buckling analysis

Figure 3: Mock-up of roof connection

Figure 4: View of underside of roof

Figure 5: Mock-up of part of the pavilion at BRE

Figure 6: Bolt cage prior to concrete pour

Testing

A 1:1 part mock-up was constructed at the Building Research Establishment's testing facility in Watford, UK, primarily to test the structure's dynamic response, both with and without the inclusion of impact dampers. Static tests were also conducted on the mock-up to enable the finite element models to be calibrated. The dynamic test consisted of a shaker that was attached to the column at mid-height. It was estimated from these tests that the intrinsic damping for the welded structure was as low as 0.2 % which is significantly less than that specified in BS 6399-2 [3] for a welded steel frame (typically a value of 0.4 % is adopted). The tests also enabled the structure's ability to resist vandal loading scenarios to be demonstrated, the proposed construction methodology to be tested and finishes and lighting to be determined.

Fabrication

1500 stainless steel holding down bolts were used to position the columns to very tight tolerances (±1.5 mm). This was achieved by the use of a "bolt cage" (a network of carbon steel angles and flats) cast into the slab, which acted as reinforcement and held the bolts in position as the concrete was poured (Figure 6).

Stainless steel is highly susceptible to weld distortion. To avoid issues arising from elements being out of tolerance, the whole superstructure was match fabricated with sections straightened after each welding procedure. To make the elements more manageable, the roof grillage was fabricated first with spigots (for attachment to the damper and the column section) prior to delivery on site.

The impact dampers in the columns control the wind induced resonances to amplitudes of around 4 mm; the columns will also exhibit some wind induced motion below this amplitude. There will therefore be some cyclic loading and potential fatigue damage of the welds at the base and head details. Therefore extra tests were undertaken to confirm that the welds were the class assumed in the fatigue calculations. Both ultrasonic and dye-penetration testing procedures were adopted to ensure the weld quality was maintained throughout.

Erection

The pavilion occupies a very constrained site and required a carefully planned programme with a very specific construction sequence and crane use. A method statement for the pavilion's erection was developed with the fabricator and 3D visualisations were produced to illustrate the erection procedure to the design team and client.

An adhesive plastic protective coating was applied along the length of the columns to protect them during transportation and erection [4]. Following completion of construction, a number of scratches to the column surface were evident at high level. A polisher was adapted such that it would automatically run up and down the height of the columns and remove any visible defects. This purpose-built machine was dubbed the “rat up a drain pipe” and ensured the full beauty of the elegant, impossibly slender columns was achieved.

Figure 8: Pavilion under construction

Figure 7: View of illuminated underside of roof

Figure 9: On-site polisher (“Rat up a drain-pipe”)

Information for this case study was kindly provided by Arup.

References and Bibliography

[1] BS 7608:1993 Code of practice for fatigue design and assessment of steel structures

[2] EN 1993-1-4: 2006 Eurocode 3. Design of steel structures. General rules. Supplementary rules for stainless steels

[3] BS 6399-2:1997 Loading for buildings. Code of practice for wind loads

[4] Erection and installation of stainless steel components, Euro Inox, 2006

Online Information Centre for Stainless Steel in Construction:
www.stainlessconstruction.com

Procurement Details

Client:	British Land
Project Manager:	M3C Consulting
Architect:	Carmody Groarke
Structural Engineer:	Arup
Main contractor:	Bovis
Steelwork contractor:	Sheetfabs

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