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Stuart Tappin

Dudley Zoological Gardens

Dudley, England | 1937

ARCHITECT/DESIGNER
Tecton Architects; Ove Arup, engineer

PROJECT DATE(S)
2011–15

PROJECT TEAM
Bryant Priest Newman Architects; Stand Consulting Engineers

CLIENT/BUILDING OWNER
Dudley Zoological Gardens

INTRODUCTION

The town of Dudley is in the West Midlands of the United Kingdom. It lies within an area that became known in the mid-nineteenth century as the Black Country, a reference to the pollution generated by the thousands of ironworking foundries and coal mines when this region was a center of industry and manufacturing. "Black by day and red by night" was how Elihu Burritt, the American consul to Birmingham, described it in 1868, and this could have equally applied in 1935 when the proposals for a zoo were first developed.

The zoo is located on a small hill below the ruins of Dudley Castle. The site was owned by William Humble Eric Ward, the third Earl of Dudley. Ward, together with a local businessman, Ernest Marsh, and Captain Frank Cooper, formed the first board of directors of the Dudley Zoological Society. Captain Cooper owned Oxford Zoo and was looking to close it and find a new home for his animals. Doctor Geoffrey Vevers, the superintendent at London Zoo, was appointed as their advisor. Vevers had recently worked with Tecton Architects, led by the Tbilisi-born Berthold Lubetkin, at London Zoo, where they had designed the gorilla house and the penguin pool with the structural engineer Ove Arup (1895–1988). Arup had recently left the contractor Christiani and Nielsen, and his involvement at Dudley was as the director responsible for designs and tenders at J. L. Kier and Company.

The directors at Dudley set a timetable for the zoo to open in the spring of 1937, which meant that design and construction had to proceed at a rapid pace. In addition to the tight schedule, there were further pressures from dealing with the Ancient Monuments Department of the Office of Works, which was concerned about the setting and integrity of the castle. There were also unexpected engineering challenges from the unrecorded and obsolete tunnels and mines once used for the extraction of limestone and coal below the site. One consequence of these factors is that it appears that much of the final design was carried out on site by the project architect, Francis Skinner, and Kier's resident engineer, Ronald Sheldrake (Allan 2012, 221). There were also compromises to the design, most notably for the bear ravine structure (fig. 4.1, post conservation view), where problems with the ground conditions reduced the three-quarter circular plan and stepped form to less than a half-circle with a level viewing platform.

The zoo opened to the public on May 6, 1937, and two weeks later the front page of the *Dudley Herald* reported, "Bewildering Bank Holiday Traffic Scenes on Castle Hill. Estimated 150,000 Visitors—50,000 Admitted" (Dudley Herald 1937). By the end of that first summer the zoo had welcomed nearly seven hundred thousand visitors. The main interest was undoubtedly the animals, but the buildings were also an attraction. For many it was likely their first experience with modern architecture.

Twelve of the original thirteen buildings constructed for animals or visitors remain; the penguin pool was demolished in 1979 (fig. 4.2). All are now listed grade II* or grade II and together they form, arguably, the most complete set of buildings of the modern movement period in the UK.[1] The national and international importance of these buildings and their perilous state led to them being placed on the 2010 World Monuments [Fund] Watch list.

THE PROJECT

The design team of Bryant Priest Newman Architects and Stand Consulting Engineers were appointed in 2011 to prepare an application to the Heritage Lottery Fund (HLF) for the repair and refurbishment of four of the structures: the entrance, the bear ravine, and a nearby kiosk, all individually listed at grade II*, and the grade II listed shop, originally known as the Station Café. They were all generally in poor condition, with some parts of the bear ravine in a very poor state with extensive areas of spalled concrete due to corrosion of the reinforcement. A range of repairs had been carried out previously, including some using polymer-modified mortars. None of these repairs had addressed the underlying causes of decay or prevented further damage, and the majority of them had failed. A

Fig. 4.1. Dudley Zoological Gardens. The repaired bear ravine, 2015.

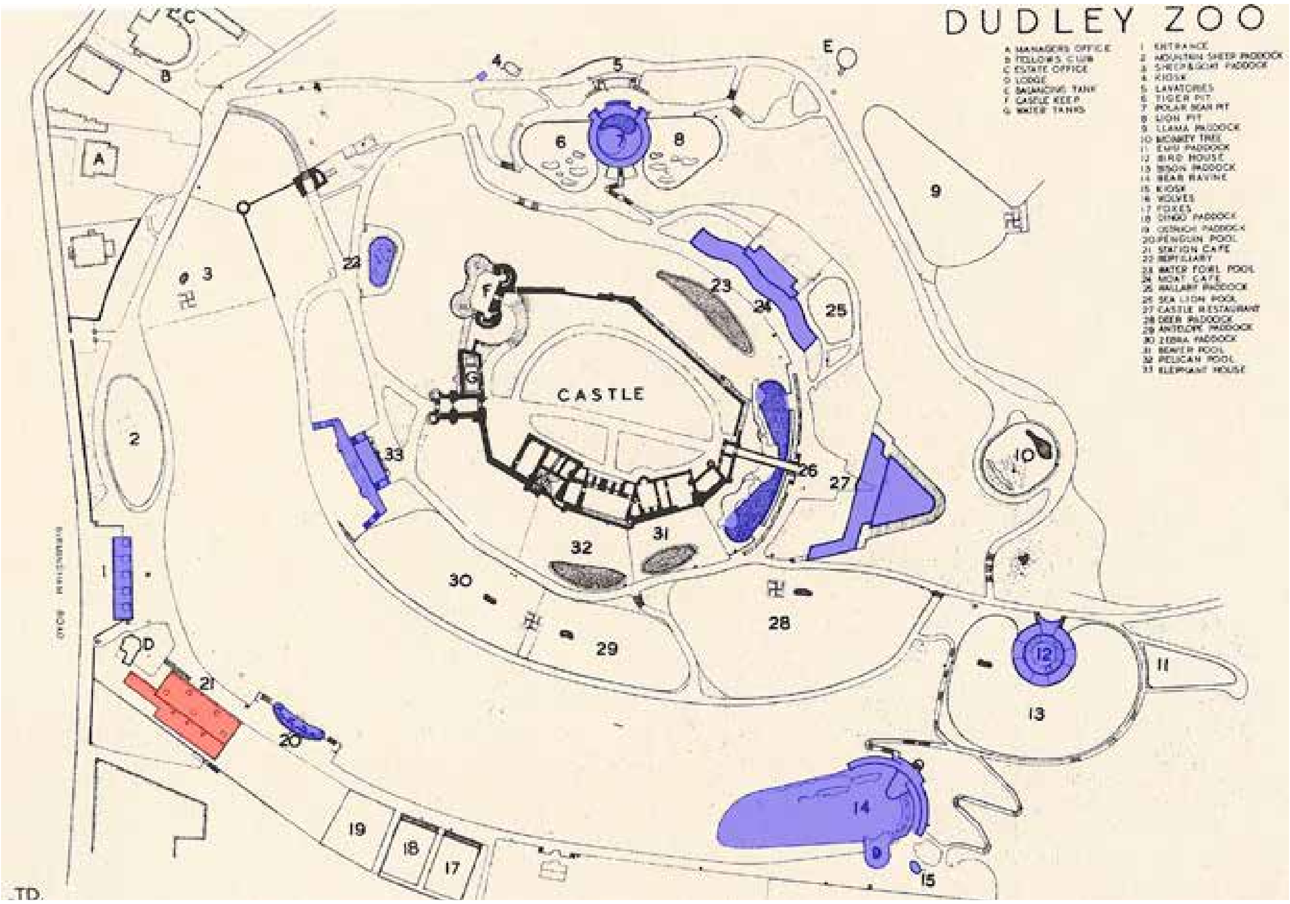

Fig. 4.2. Site plan showing the layout of the Tecton-designed buildings: 1) entrance, 21) Station Café, 14) bear ravine, 15) kiosk. Map courtesy Dudley Zoological Gardens

number of earlier reports concluded that a combination of major repairs and partial rebuilding was required.

None of the structures were in use as originally designed, and they were all in a state of neglect. The original entrance was located on Castle Hill, close to the Dudley town center. This was ideal when visitors arrived by bus or tram, but by 2009 that entrance was partly boarded up, as the majority of visitors were arriving by car and parking on the opposite side of the hill, entering near the former Station Café. This building had seen a number of different uses, and in 2011 it was serving as the zoo's souvenir shop. Both the bear ravine and kiosk were disused.

INVESTIGATIONS: BACKGROUND RESEARCH, ANALYSIS, DIAGNOSTIC WORK, TESTING, AND TRIALS

From the outset, the client agreed that the approach to the project would be the same as that for pre-twentieth-century historic buildings. This involved first gaining an understanding of the form and condition of the structures in order to target repairs based on the principles of using compatible materials and the minimum amount of intervention into the historic fabric wherever possible. A key part of this approach was not to repair unless there were clear signs of damage. For example, poorly formed construction joints and local irregularities in the surface from poor compaction of the concrete would be retained as a record of how the structures were built.

The appraisal began with a visual assessment of the structures and a review of the historic documents held at the zoo's archive. This extensive record allowed us to build up a detailed picture of the structures, their intended uses and original forms, and an indication of the original color schemes. Copies of the original Tecton drawings clearly outlined each structure's intended form. Photographs taken soon after completion showed materials and finishes, and even though they were black and white, the tones provided an indication of the use of color. These photographs also helped to identify elements that had been altered. For example, the "ZOO" lettering on the front of the entrance kiosks was thought to be original, but a review of the archive found that the Z had a slightly different shape on the corners, revealing that at least that one letter had been replaced at a later date. The archive contained visitor guides from every year dating back to its opening. On the souvenir program from 1937, a hand-painted image of the entrance clearly showed red lettering with a white border.

The next stage was a visual assessment of the structures. Questions posed included: How would they have been designed? How did they build with reinforced concrete in the 1930s? What was the quality of the construction? How had they been altered or repaired? From this process, it was possible to get a general "feel" for the structures, assess if the defects were generic or specific, and identify if there were particular structural issues.

The entrance, with its undulating reinforced concrete roof structure, was now used only during peak times. Several of the entrance building's five brick kiosks had been boarded up, the turnstiles had been removed, and each element of the structure had been painted with a variety of inappropriate colors. The proposal was to strip away all of the added items, reopen all of the kiosks, and reinstate the original design.

Of the four buildings, the Station Café was the most changed since 1937. Through the years the building had been altered as its use changed to a fish and chips shop, a nightclub, and finally the zoo's souvenir shop. The original open, windowless pavilion style of the building had been lost amid the changes and clutter, and partitions had been installed enclosing sections of the building for storage. Other areas were simply abandoned. The proposal was to remove all of the later additions and reinstate the open layout. In accordance with the wider master plan for the zoo, the shop was to provide a proper entrance for visitors and an interpretation space to explain the history of the zoo and its buildings (fig. 4.3).

The bear ravine and kiosk were the most unchanged due to the fact they had been left unused for many years. This neglect meant that the bear ravine in particular was in very poor condition, with large sections of concrete missing and exposed reinforcement. The approach for these two structures followed the principle of reinstating the original design, although the enclosure will not be used to house bears again.

The structural assessment found that the majority of the problems with all four buildings were due to corrosion of the reinforcement. In many areas, the cover to the reinforcement was much less than the 1 in. (25.4 mm) cover for main bars and ½ in. (12.7 mm) for secondary reinforcement recommended in the *Report of the Reinforced Concrete Structures Committee of the Building Research Board with Recommendations for a Code of Practice of the use of Reinforced Concrete in Buildings* (Department of Scientific and Industrial Research 1933).

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Fig. 4.3. The shop before the works, 2011

Fig. 4.4. A typical area of damage to the underside of one of the entrance canopy slabs, 2012

There were, however, some areas with structural problems generated by their daring form. At the entrance building, transverse cracks were identified in similar locations on the top faces of each of the five curved slabs. There were also concerns about the integrity of the connection between the tops of the solid steel columns and the roof slabs. At the bear ravine, there were cracks in the side walls of the cantilevered viewing platform, a longitudinal crack in the top face of the slab above a downstand beam, and a distinct bounce when walking at the outside edge of the platform.

Concurrent with the initial work to prepare a report for the HLF, a series of investigations and tests were carried out by Rowan Technologies. Schmidt hammer tests found the compressive strength to be mostly in the range of 40 to 55 N/mm², with only a few readings between 30 and 40 N/mm². All the readings were greater than the minimum cube strengths for the four categories of ordinary grade concrete listed in table 1 the 1933 Building Research Board report (Department of Scientific and Industrial Research 1933, 21). This, combined with our own assessment, confirmed that the strength of the concrete was generally not a concern.

Tests on samples of the concrete found the chloride and sulfate levels to be within acceptable levels. The main issue was the widespread, inadequate concrete cover to the steel reinforcement, with carbonation depths reaching up to 1½ in. (40 mm). The curved roof slabs of the entrance generally had a cover on the top surface of between ½ and 2½ in. (13 and 65 mm) with only occasional signs of corroding bars on this face. On the undersides of the roof slabs, however, the cover meter survey was hardly required, as large areas of reinforcement were clearly visible through the many layers of paint. A fundamental question was, why was the concrete cover to the reinforcement so poor?

There is little information from the 1930s about how reinforcement was to be supported during concreting. One contemporary reference, in *Cassell's Reinforced Concrete*, mentions the use of notched timber templates that "can be removed shortly after the concreting has begun, quite a small quantity of concrete sufficing to hold the rods in place" (Jones and Lakeman 1920, 140). If this was the method used here, then the undulating shape of the slabs meant it was almost inevitable that the bars would slump toward the bottom of the wet concrete and rest on the shuttering. We can only surmise that the pressure to open the zoo to the public led to a make-do approach, with a render coat and paint applied to hide the exposed reinforcement (fig. 4.4).

There were also areas of exposed reinforcement and spalled concrete present at the shop and kiosk buildings, but the greatest damage was to the bear ravine. On the

Fig. 4.5. The bear ravine prior to repairs, 2011. Photo: Tony Hisgett / Courtesy Wikimedia Commons, CC-BY-2.0

Fig. 4.6. Detail of the bear ravine prior to the works, 2012

cantilevered viewing platform there were large areas on both faces of the parapet where the concrete had fallen away and exposed the corroded reinforcement behind. The extent of corrosion to some of the circular hollow steel columns around the stairwell to the upper viewing level was of sufficient concern to prompt immediate installation of temporary props (figs. 4.5, 4.6).

By the end of this initial appraisal, the report to the HLF placed the structural defects into two broad categories. The majority were due to poor-quality construction and subsequent deterioration, with a second, smaller category of damage that indicated structural issues that would require a more extensive intervention. The initial appraisal also confirmed that the proposal to avoid modern polymer-modified

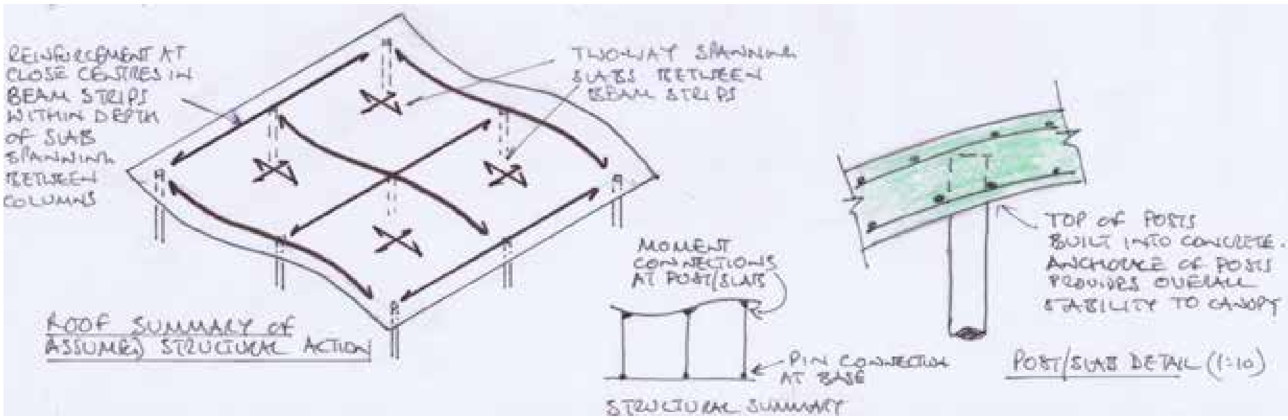

Fig. 4.7. Structural summary of entrance roofs

materials and instead use traditional concrete for the repairs wherever possible was feasible. As with more traditional forms of construction, the use of compatible materials reduces the risk of future differential movements due to thermal expansion and contraction or changes in the moisture content. In addition, for listed structures with exposed concrete like these, a standard concrete mix will provide a closer visual match to the original fabric. This approach has been advocated by the authors alongside the Twentieth Century Society since 2009 and promoted at the annual course on concrete conservation at West Dean College in West Sussex. The tendering of the project at Dudley also coincided with the publication of an English Heritage book on the conservation of concrete that recommends a similar approach (Odgers 2012).

The next stage, begun in early 2013, was to undertake trials on part of the entrance to ascertain the best method of removing the layers of paint while maintaining the concrete's surface texture and board marks. Abrasive cleaning with varying types of blast medium and air pressures were tested until the best balance of effective paint removal and limited damage to the existing surface was found. A trial repair was specified on an area of spalled concrete on the shop to explore methods of how best to remove the damaged concrete and deal with the limited concrete cover to the reinforcement, trial the proportions for the cement-to-aggregate repair mix, and test the best methods of matching the surface finish. While carrying out cleaning and repair samples on the structures, a paint survey was undertaken to analyze the layers of paint present on the different surfaces. This microscopic analysis established the color history of the structures and, more importantly, the original finishes and colors.

HOW THE STRUCTURES WORK

The Entrance

The entrance to the zoo is formed of five undulating reinforced concrete slabs above individual ticket kiosks that are built of brickwork and timber. Each roof slab is 6⅞ in. (175 mm) thick and approximately 275 by 275 in. (7 by 7 m) on plan. The slabs have a projecting edge beam on three sides that prevents rainwater runoff from staining the outside edges. The slabs are supported on nine solid steel posts, each 3½ in. (90 mm) in diameter, on a grid of 118 by 118 in. (3 by 3 m). The posts bear onto shallow concrete pad foundations. Two layers of ½ in. (12.7 mm) plain round bars that were observed close to the surface of the soffit indicated that they were designed as two-way spanning slabs. The overall stability is provided by a moment connection between the head of the columns and the slab. The entrance is on sloping ground, and the design cleverly exploits this by having the end of one slab overlapping the next. At each overlap, the three edge columns pass through the lower slab and into the slab above, a detail that provides an additional restraint against lateral movements. This is summarized on the extract from drawing number EC 01 (fig. 4.7).

The Station Café / Souvenir Shop

The souvenir shop is a more conventional structure with reinforced concrete walls 4 in. (100 mm) thick and three rows of circular reinforced concrete columns. These columns support the roof, which is formed by a slab 4⅞ in. (125 mm) thick and upstand beams. Three of the internal concrete columns had been removed and replaced with steel beams and columns. Once the works started, it was found that these alterations had been made to provide a lowered dance floor area during the building's brief life as Bentley's Night Club in the 1970s.

The Bear Ravine and Kiosk

The bear ravine sits into the hillside with the upper level formed by flat slabs supported on mushroom-head columns with thin reinforced concrete walls and hollow steel columns around the stairwell. The cantilevered viewing platform is a more complex structure. The 5⅛ in. (130 mm) thick slab is supported at the rear by the concrete walls to the bear pens below and propped at mid-span by a downstand beam 13¾ in. (350 mm) deep by 7⅞ in. (200 mm) wide. The outside edge of the slab is connected to the 4 in. (100 mm) wide concrete parapet wall that acts as a deep beam that is anchored back to the main structure at each end. The structural action of the parapet as a beam was confirmed when lines of twisted reinforcing bars were observed close to the top of the beam. These are Isteg bars, a patented reinforcement that was developed in Germany and introduced to the UK in the early 1930s (Emperger 1934). The system used pairs of plain steel bars twisted together so that the cold-working increased their tensile strength by about 50%. They were advertised for use where a higher tensile strength, compared to ordinary steel bars, was required. Spandrel panels below the parapet at each end act as a prop to the parapet walls and provide a support to each end of the downstand beam. Both faces of all the parapets have a ribbed finish, and a small piece of corrugated steel found during the repairs confirmed that this finish was cast.

The small kiosk near the bear ravine uses a combination of reinforced concrete walls and hollow circular steel posts to support the 5⅞ in. (150 mm) thick elliptical roof slab.

PHASING AND PROCUREMENT

A strategy for phasing the works was developed, beginning with the entrance and the souvenir shop. As the ticket office in the shop was to be closed during the refurbishment, the works to the entrance also had to be phased to maintain access for visitors. These are the first two buildings that visitors see, so beginning the works there provided an immediate impression that the zoo was improving as an attraction and caring for its building stock. Another consideration was to use these two buildings as a learning exercise for the project team and contractor before embarking on the more extensive works required on the bear ravine. There was also a concern that the scale and extent of repairs needed on the bear ravine could take a sizable slice of the funds to the detriment of the other buildings.

The majority of the works to the entrance involved concrete repairs, but the shop was a more general refurbishment with the concrete repairs representing just one part of the overall scope of works. Based on this, it was decided to have a tender that included a general contractor and concrete repair specialists. In this second group, we included contractors who deal exclusively with concrete repair and specialist stonemasons experienced in concrete repairs. A local contractor from this second category was appointed.

The grant from the HLF included the cost of a clerk of works and two apprentices who would study part-time and gain practical experience by working alongside the contractor.[2] The aim was for the apprentices to remain at the zoo at the end of the contract to deal with ongoing repairs and maintenance of the other structures. Finding a clerk of works proved to be more difficult than envisaged, and although candidates were interviewed, no one suitable had been found by the time the work started on-site. However, the eventual outcome proved to be very beneficial, as described below.

The Procurement Process and Information Provided

The tender or procurement processes and the information developed through them are important parts of any conservation process. Thoughtfully managed, they can greatly assist in developing more detailed scopes of work and helping to identify suitable contractors for the work. The Dudley Zoo tender package included drawings and a specification for an initial strip out that facilitated more detailed inspections and trials. This was informed by research of historic documents and site investigations, and contained detailed drawings that identified areas to be removed—and, equally important, areas and items to remain untouched.

The findings from the various tests, trials, and investigations were all incorporated into the tender package. This included drawings of the existing structures that recorded the areas of damage seen and those areas still covered with finishes where defects could be expected. Clauses in the tender package set out a process of investigations followed by a review of the findings by the project team before final details could be issued. This included most of the inside of the souvenir shop, which continued to trade until the start of the works. Plans and details for the proposed works recorded the known defects and indicated allowances for repairs to be confirmed once the structure was exposed.

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The repairs were cross-referenced to the specification, which provided details and methodologies for a number of types of concrete repair. These were referenced to the position (top, side, or soffit) and to the anticipated depth of the repair. This allowed the contractor to cost the scope of works and identify which repair to use for each location.

The standard repair for use on the top of level surfaces and vertical faces was a 1:2:4 mix of cement to sand to aggregate, to match the original concrete. Aggregate up to ⅜ in. (10 mm) was used in the mix for larger areas of repair work. Shallower repairs used a 1:3 or 1:4 mix of cement and graded aggregate up to ⅛ in. (5 mm) in size. The procedure was for the edges of the damaged concrete to be cut out using a small disc cutter, taking care not to cut the reinforcement. The arrises were slightly undercut to improve the mechanical adhesion of the repair material. The loose and damaged concrete was specified to be removed so that the entire surface of the exposed reinforcement bars was accessible. These were then cleaned to a bright and shiny finish, given an anticorrosion coating, and covered with a cement slurry immediately before the concrete was placed. In general, the concrete had a plain finish, but the repair was required to match the existing finishes, including lines of joints between the original shutter boards.

There were some locations, mostly to the soffit of the slabs and beams, where a repair using a traditional concrete mix was not possible without significant implications for the historic fabric. Either it would involve the removal of all the existing concrete to re-cast around retained reinforcement, thus sacrificing significant amounts of historic fabric, or the thickness of the slab would have to be increased to place concrete from below in order to provide an acceptable cover to the bars. This option would also have structural implications from the additional weight of concrete and would have significantly changed the appearance. Both of these options were rejected. Instead, a ⅛ in. (4 mm) thick polymer-modified repair render was applied to the cleaned and primed surface and then manually worked on the surface to match the surrounding, original board marks. For the entrance roof slabs, the tender drawings provided an allowance for this render coating to all of the soffits.

The soffit within the shop was hidden by a suspended ceiling, but an adjacent storeroom showed a considerable amount of exposed reinforcement. It was believed that the rest of the soffit would be in similar condition, and this proved to be the case once all the finishes were removed. For reasons of economy, it was agreed that works could be deferred to the areas of the soffit where the damage was not structurally significant, and only the essential repairs were undertaken. This seemed a reasonable approach, as new roof coverings meant the structure should remain dry; a plasterboard ceiling was also proposed that covered the majority of the soffit. This ceiling was also used to hide the services, such as cabling for new lighting and safety systems. A detail was developed to set back this new ceiling inside of new glazing around the perimeter of the building and allow the underside of the roof slab to be visible.

CONSERVATION

The contract for the entrance and souvenir shop started in September 2013, beginning with the strip out and cleaning. The trial cleaning on the underside of the entrance slab had exposed a blue color, and when the entire structure was cleaned, it was found that this blue was used over the entire soffit. The edges however, showed no sign of blue. Microscopic analysis found a layer of dirt on the concrete beneath the first layer of paint, indicating that it had initially been left untreated for some time.

The stripped soffits revealed extensive corroded reinforcement and spalled concrete, confirming that the tender allowance to treat all the soffits was required. Another tender-stage allowance was to break out the concrete around a number of the column heads, install additional bars, and re-cast with new concrete. A trial investigation was carried out to the column head with the greatest amount of damage to the concrete. After the slab had been temporarily supported and the concrete locally removed, the reinforcement around the column was found to be in poor condition. The column was also found to have a 7 by 7 by ¾ in. (180 by 180 by 20 mm) thick welded head plate that had no significant signs of damage. For the trial repair, the hole formed through the slab was filled with new concrete. Elsewhere the contractor was able to repair the areas from below, either with a traditional concrete repair placed by a letterbox shutter, or with the polymer-modified render repair mix.

As mentioned earlier, there were cracks on the top surface of each canopy of the entrance building, which were on the hogging curve of the slabs. There were no obvious structural reasons for this, and the most likely cause was small-scale folding of the slab from thermal expansion and contraction. As it is not possible to stop these movements, the initial suggestion was to fill these cracks with a soft lime mortar and accept that this was an area that would need a higher level of ongoing maintenance. However, it was decided that water ingress into the slab had to be prevented to inhibit damage to the newly repaired and painted soffit.

The top of the entrance canopies had never been waterproofed and instead relied on a shallow fall to a small outlet

Fig. 4.8. Repair to the entrance canopy slab, 2014

Fig. 4.9. The entrance following conservation work, 2015

and drainpipe that ran through the kiosks below, although the majority of rainwater ran over the edges of the roof slabs. The concrete was, unsurprisingly, damp. A temporary covering was placed over each section to allow the structure to dry prior to any finish being applied. The tender package included provision to coat the top surface with a silane to stop water penetrating through the concrete. However, through further discussions with various specialists, it was concluded that any ponding water would eventually find its way through into the structure.

A roof covering was therefore proposed and the design criteria included the need to be reversible and to accommodate thermal movements. It also needed to be visually acceptable, as the roof of the entrance building can be seen from the top of Castle Hill and nearby the chair lift. No flashings or mechanical fixings could be used, as this would impact on the slender edge detail of the wave forms. With the exposed location of the entrance, the new covering would also need to resist uplift pressures. Through discussions with the project team and agreement with the local conservation officer and English Heritage (now Historic England), a liquid applied membrane was selected. Resin-set quartz was then applied to the top to match the surface color and texture of the existing concrete. The aggregate for the quartz was sourced from a local quarry to match the tone and consistency of the concrete. The resulting view from the chair lift is of five seemingly untreated concrete canopies (figs. 4.8, 4.9).

At the souvenir shop, the initial work involved the stripping out of all the internal fixtures and fittings and the removal of the external roof finishes. Once completed, we found that the concrete roof structure was in much better condition than had been expected and only required a few local patch repairs. A single-ply membrane was installed as a waterproofing barrier atop new insulation. The infilled circular roof lights were reopened. Combined with the removal of the non-original brickwork above the timber window frames, this completely changed the feeling of the internal space, flooding it once again with natural light (fig. 4.10).

Part of the underside of the roof slab within the storeroom had been removed, and once all the finishes and the black paint (another remainder of the nightclub) were removed, the investigations could be completed and the scope of repairs finalized. The main issue with the underside of the slab was the poor concrete cover to the bars and a number of areas with exposed reinforcing bars that needed to be repaired. As most of the soffit was to be hidden behind a new suspended ceiling, a different approach was adopted for isolated exposed bars and hairline cracks.

Fig. 4.10. The shop interior after the works, 2014

Fig. 4.11. The shop upon completion of repairs, 2014

As mentioned above, in order to make the best use of available funds, it was agreed that if the current damage was not structural, not at risk in a fire, and not likely to deteriorate in the future, it would be left untouched.

The steel beams and columns that had replaced the two original concrete columns were removed and new steel columns installed onto new concrete pads that were placed around the original damaged foundations. Steelwork was used rather than re-forming in concrete because of the speed and ease of installation and the significantly lower cost. There was also a concern that modern concrete casting techniques might look too good next to the existing columns. Instead, a mold was taken from one of the original columns and used to create a glass-reinforced plaster casing, which was installed in two half sections around the new columns with the joints mimicking the cast lines in the original shuttering.

The most significant repair works to the shop were to the adjacent toilet block. A section of the cantilevered roof slab above one of the entrances was so friable that the concrete could be unpicked by hand. The rebuilt section was considered a piece of new construction and was designed for dead and imposed loads using modern codes. This required additional reinforcement alongside the original rebar before the section was re-cast to the original profile. To the rear of this building were two high-level windows that ran the full length of the building. Each of these openings was 236¼ in. (6 m) long and had a slender 5⅛ by 5⅛ in. (130 by 130 mm) reinforced concrete mullion at mid-span. Once the damaged concrete had been removed, the reinforcement to one mullion was found to be in a reasonable condition. After cleaning and coating the bars the mullion was re-cast with new concrete. The bars on the second mullion had lost a significant amount of their cross section and we prepared two repair options: re-casting in concrete with additional bars or replacing with a steel hollow section. After discussions within the project team and with English Heritage, the option for a steel post was agreed and installed.

The works to the entrance and shop were substantially completed on schedule and both opened in time for Easter 2014, to much acclaim (fig. 4.11). The zoo now knew how much money was left for the works to the bear ravine and kiosk. Of equal importance, the design team had tested the processes of repair and could develop the best strategy to tackle the more extensive repairs.

Unfortunately, the performance and general level of management by the contractor who had carried out the concrete repairs to the entrance and shop had deteriorated during the course of the project. One consequence of this was that one of their foremen applied for the position of clerk of works. His expertise in concrete and stone repair, and obvious enthusiasm for the project, presented a new possibility. Rather than act in a monitoring role as a clerk of works, he was employed by the zoo to lead the concrete repairs with an assistant and the two apprentices. The zoo now had direct control over the costs and quality of work. The same general contractor who had worked on the first phase was used to provide the site mobilization and scaffold. The concrete cleaning, painting, and waterproofing were procured as separate packages by the zoo.

In contrast to the entrance and shop, much of the concrete surface to the bear ravine has a delicate corrugated finish (fig. 4.12). To avoid damage from abrasive cleaning, other techniques to remove debris and paint were tested; at the end of the trials, a two-stage approach was agreed. A ThermaTech superheated steam system was used to remove all organic contaminants and the majority of the coatings. Coatings that were more stubborn were treated with chemical strippers and carefully removed by hand. Areas that did not respond to this treatment were cleaned using a very

Fig. 4.12. Detail of damaged concrete to the bear ravine's parapet during repairs, 2014

Fig. 4.13. Bear ravine during the repair works, 2014

light abrasive program utilizing both wet and dry blasting. In a few areas, it was not possible to remove all the coatings without significant damage to the surface of the concrete, and it was agreed to leave these coatings in place.

The initial feasibility-stage review of the bear ravine had identified significant structural issues with the cantilevered viewing platform. Based on this, an allowance was made in the cost plan to remove all the concrete to the parapet and place additional reinforcement alongside the existing bars before the parapet was re-formed with new concrete. Allowance was also made for stiffening the cantilevered slab with a layer of mesh reinforcement within a high-strength cementitious render on the top and bottom faces.

With the slab propped by a support scaffold, the layers of paint were removed by the steam cleaning process along with loose and damaged areas of concrete. This revealed that the underlying concrete was in a much better condition than anticipated (fig. 4.13). This enabled the parapet to be repaired rather than rebuilt, as shown in figure 4.11. An alternative to the addition of mesh reinforcement to the slab was also explored.

Investigations found two layers of 9.5 mm (⅜ in.) diameter bars at 4 in. (100 mm) centers near the bottom of the slab. The downstand beam had six Isteg bars at the bottom and 9.5 mm diameter links at 200 mm centers. Isteg bars were also found in the parapet wall, as can be seen in figure 4.5.

There is no record of the original calculations and there are, unsurprisingly, no specific guides for the imposed loads to be used in the design of a structure like this. The 1933 Building Research Board report (Department of Scientific and Industrial Research 1933, 56) has a category for "churches, schools, reading rooms, art galleries and the like" that gives an imposed load of 80 lb per square foot (4 kN/m^2). The zoo does plan to allow controlled use of the viewing platform for visitors, but 4 kN/m^2 seemed excessive. A notional imposed load of 3 kN/m^2 seemed more reasonable on the basis that visitors could congregate along the prow of the platform. We also wanted to provide a structure that was stiffer than the original to reduce the risk of deflection-induced cracks, and make the platform feel more secure so as not to cause undue concern to visitors.

This imposed load was used to calculate the bending moments, shear forces, and span-to-depth ratios for the slab and beam. This found that the slab would theoretically be able to support the load, but the beam would, again

Fig. 4.14. Bear ravine after the repair works, 2015

Fig. 4.15. The repaired bear ravine, 2015

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theoretically, fail in bending and shear. From a review of the calculations and the damage viewed on-site, it was concluded that remedial work should be targeted to address three areas: the general lack of stiffness to the slab; the lack of top reinforcement as indicated by the crack above the downstand beam; and the poor connection between the ends of the downstand beam and the spandrel panels.

This led to the proposal that remedial works be carried out using carbon fiber bonded to the concrete to provide the additional strength without any significant change to the thickness of the structure. Once the principle of this approach had been agreed upon by all parties, the works were discussed with a carbon fiber specialist contractor, and one of their projects was visited to see how the carbon fiber sheets were fixed onto reinforced concrete. The values of the existing and proposed bending moments and shear forces were provided to the specialist contractor and were used by them to develop their design. Their proposal used two layers of 1 mm thick carbon fiber sheets that were applied locally to the slab to enhance the hogging and sagging bending moments. A single layer of sheeting was applied to stiffen the downstand beam. Carbon fiber cables

Fig. 4.16. The kiosk with bear ravine behind, following repair works, 2016

were installed through two small holes drilled in each spandrel panel and then splayed out to link both sides of the beam with the outside faces of the spandrels. An unscientific heel-drop test found significantly less bounce in the platform than before the repairs. The surfaces of the walkways and viewing platform and the top of the kiosk canopy were treated with the same liquid membrane and quartz layer that had been used on the entrance canopies.

The concrete repairs to the bear ravine, though on a much larger scale than those undertaken on the other buildings, followed the same philosophy. Cement and aggregate mixes were used on all vertical and horizontal surfaces and the polymer-modified repair mortar was used for the undersides of the slabs. The quality of the repairs to the corrugated finish of the parapet walls was a significant achievement by the on-site team. A series of tools were developed, ranging from a float profiled by a latex mold taken from an original section of corrugated metal shuttering to a bespoke timber profiled float. The most useful tool turned out to be a simple round timber dowel that was used to line the profiles through. When breaking out the damaged concrete any sound surfaces were left in place, no matter how small. These areas ensured that the rhythm of the corrugation matched the existing pattern (figs. 4.14, 4.15).

The structural repairs to the nearby kiosk were relatively minor. The hollow steel columns had all corroded at the base, which meant that the support to the roof relied on friction where the columns passed through the reinforced concrete slab that formed the counter to the kiosk. Temporary props were installed before the permanent repair of steel sleeves were welded around the base of each post to reinstate the original support (fig. 4.16).

The works were completed early in 2015. Following this, the on-site team began work on the sea lion pool and the former reptiliary, now home to meerkats, which is the only enclosure never to have been painted. This work has been carried out in stages with the meerkats remaining in place; moving a colony is known to disrupt breeding by up to five years.

These repairs now form an important stage in the site's history. To record and communicate this to visitors, a section of the souvenir shop now houses an interpretive display telling the story of the zoo and its Tecton buildings. The display uses historic images of the zoo, information on its architectural significance, and a description of the repair works that have been undertaken. The surviving section of the Station Café's original, sinuous concrete counter, with its exposed reinforcement, is part of the exhibit.

During the works, it was proposed that ongoing monitoring of the repairs be undertaken by English Heritage. This would help to accurately assess the durability of the repairs and equip the organization with important information to help develop an understanding of best practices for concrete repair and conservation. The monitoring, which began in 2015, includes a photographic assessment at one-, three-, five-, and ten-year intervals and corrosion rate mapping pre- and post-repair to assess changes in the corrosion rates of the adjacent reinforcement. Concrete hardness tests using a Schmidt hammer will be undertaken on repaired and surrounding concrete, and samples will be tested to assess changes in the alkalinity at various levels, through the depth of the concrete. Measurements at set distances away from the repair will also test whether the high alkalinity of the new concrete repairs will migrate into the adjacent original concrete.

CONCLUSIONS

The works to the four structures at Dudley Zoo have demonstrated that it is possible to successfully carry out conservation-based repairs to historic reinforced concrete structures. The overall program was set up to allow adequate time during both the design and the construction stages to carefully consider what works were required and how best to execute them. Options were prepared to evaluate key issues such as how much original fabric can be retained and the maintenance of the original appearance. After weighing the implications of each option, a pragmatic approach to the limited use of modern repairs was agreed upon and adopted.

The majority of the defects were due to poor concrete cover to the reinforcement. The repairs involved fully exposing the reinforcements so they could be cleaned and coated, with either an anticorrosion paint or a cement slurry, before the new concrete was placed. This approach also provided some clear space so that by hammering the bars it was possible to improve on the amount of concrete cover. Wherever possible, the repair works used cement to aggregate mixes that are compatible with the original concrete. This was feasible where the concrete was being placed to the sides or to a sky-facing surface. It was more problematic for repairs to the undersides of beams and slabs where the wet repair material was working against gravity.

A key part of the success of the project was the very close collaboration between the client, architect, engineer, and contractor, alongside regular reviews with the regulatory heritage agency (English Heritage, now Historic England) and other key stakeholder groups such as the Twentieth Century Society. This is especially important where a "light touch" approach for listed buildings is applied. The project has been fortunate to have a client who has a long-term commitment to the buildings. The zoo understands that it is not possible to solve all the issues with these buildings and structures "once and for all." Instead, careful repair and ongoing regular maintenance is the appropriate approach.

The project included the training of apprentices in the art of concrete repairs; consequently, the zoo now has an on-site team who can deal with any defects at an early stage. As the conservation-based approach to the repair of historic concrete structures is relatively new, Historic England is undertaking a program of monitoring and testing. This will gauge the effectiveness of the repair works and help to inform future repairs to historic reinforced concrete structures. A number of seminars on the works have been given to interested parties with the aim of explaining the approach and specific works and disseminating the repair methods. It is hoped that the approach taken here can act as an exemplar for other historic reinforced concrete structures in the UK and elsewhere.

NOTES

1. Historic England lists historic buildings in three categories: grade 1 are of exceptional interest, grade II* are particularly important buildings of more than special interest, and grade II are of special interest.
2. The clerk of works on a construction project is responsible for ensuring that construction materials and workmanship are carried out in accordance with architectural and engineering specifications and that projects meet safety standards. The clerk of works also monitors the project's budget and progress against what is enumerated in the contract.

WORKS CITED

Allan, John. 2012. *Berthold Lubetkin: Architecture and the Tradition of Progress*. London: Artifice.

Burritt, Elihu. 1868. *Walks in the Black Country and Its Green Border-Land*. London: Sampson Low.

Department of Scientific and Industrial Research. 1933. *Report of the Reinforced Concrete Structures Committee of the Building Research Board with Recommendations for a Code of Practice of the Use of Reinforced Concrete in Buildings*. London: His Majesty's Stationery Office.

Dudley Herald. 1937. "Bewildering Bank Holiday Traffic Scenes on Castle Hill." *Dudley Herald*, May 22, 1937, front page.

Emperger, F. 1934. "The Application of High Grade Steel in Reinforced Concrete." *Structural Engineer* 12 (3): 160–83.

Jones, Bernard Edward, and Albert Lakeman, eds. 1920. *Cassell's Reinforced Concrete: A Complete Treatise on the Practice and Theory of Modern Construction in Concrete-Steel: With a Section on House Construction in Concrete Blocks and by Reinforced Pre-Cast Methods*. New and enlarged ed. London: Waverley.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. London: English Heritage; Farnham, Surrey, and Burlington, VT: Ashgate.