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# TECTON BUILDINGS (DUDLEY ZOO)

(Long Term Monitoring of Like-for-Like Repairs – Assessment in 2022)

## 1. Introduction and Background

A group of thirteen reinforced concrete structures were built in the period 1935 to 1937 at Dudley Zoo (DZG) by the Tecton Partnership, led by Berthold Lubetkin. The condition of the reinforced concrete had been slowly deteriorating since the latter part of the 20$^{th}$ century. DZG was successful in being awarded an HLF grant in 2013 and the repairs and conservation started towards the end of 2013. The first building to be conserved was the gift shop, which was subsequently turned into an entrance hall. The second building was the original entrance gates which were retained to provide a 'front' for the Zoo. Both of these buildings were successfully repaired and conserved. The next Tecton buildings to be repaired were the Bear Ravine and the associated kiosk. The Bear Ravine had been derelict for many years and was in a very poor condition with extensive decay of the reinforced concrete. This building was successfully completed in 2014. Finally, the Meerkat enclosure was repaired and conserved in 2015. In order to monitor the long-term performance of the like-for-like concrete repairs, RTL was tasked by Historic England and DZG to undertake monitoring of the repairs (and adjacent original concrete). This particular monitoring work was funded by DZG.

Monitoring mainly used NDT techniques, although drill samples (for subsequent laboratory analyses) were taken in 2014. A significant amount of images have been taken over the years so that repaired and original concrete surfaces could be further assessed in future years. This monitoring programme was initiated in 2014 and this work is likely to go on for a number of years to inform future repairs to historic concrete. The monitoring effort is also assessing if the repairs result in decay to the adjoining (original) concrete by a process termed 'the incipient anode or halo effect'. Monitoring points (stainless steel connections to the embedded steel reinforcements) were made on repaired areas on both the Bear Ravine and also on the Meerkat Enclosure to assess for this effect.

## 2. Site Visit (Kiosk and Bear Ravine)

The seventh annual site visit was made to Dudley Zoo on the 4$^{th}$ August 2022. The Covid pandemic in the years 2020 to 2022 had resulted in the annual monitoring inspection for 2021 being missed out. The previous monitoring inspection was in December 2020.

The inspection work entailed assessing the visual condition of the repairs and taking corrosion rate measurements on both the Bear Ravine and the Meerkat enclosure. The weather was hot (between 19 to 23°C) and very dry on the day and the previous few weeks had also been very hot with no significant rainfall for many weeks. The previous inspection (in 2020) had found significant moss growth on all (parent and patch) concrete surfaces. This was still present, but DZG employed cleaners on the inspection day to clean this moss off all concrete surfaces and also clear all drainage channels to prevent rainwater retention on RC surfaces.

*Visual Assessment* – The kiosk was visually assessed. The repairs were still in an excellent condition and no significant cracking or delamination was noted in any of the repaired areas, Figure 1. There was a fine crack on the top counter to the kiosk leading out from a steel column, Figure 2. This had first been noticed in 2020 but it didn't appear to have increased in width. This is either a thermal movement crack (difference in thermal expansion of the steel and concrete) emanating out from the embedded steel post or possibly a small amount of ongoing corrosion of the 'embedded parts' of the steel column which is expanding and cracking the concrete counter.

The Bear Ravine was visually assessed and from a distance this also looked to be in a good condition eight years after the repairs, Figure 3. However, there were a few problems noted in 2020 when the repairs were examined in detail. Shrinkage and sometimes moss growth (in fine cracks) was noted in a few areas of the top balustrade rail on the 1$^{st}$ floor (shown in previous reports). Cracks were also identified in some of the corners of the balustrade plates, most possibly due to thermally induced movement between the repairs and the parent concretes. Cracks were also noted to the areas of repair on the balustrade on the ground floor. Cracking to the circular columns was also noted at the Bear Ravine. All these defects were first identified in 2017 (some 3 years after the Bear Ravine had been completed). Re-assessment of these areas in 2022 showed that some of these defects are now starting to worsen.

A number of cracks were noted to the central areas of the parapet wall to the prow of the Bear Ravine, Figures 4 and 5. Cracks were also noted to repair patches to the fluted section of the ground and first floor parapet walls, Figure 6. Some of these defects had first been seen in 2020 but the cracks now appear to be increasing in width and becoming more extensive.

The patch repair to <u>test areas</u> 1 and 4 at the Bear Ravine had suffered problems soon after they had first been installed in 2014, Figures 7 and 8. Both areas had reportedly been repaired using a lightweight repair mortar (Renderoc) following instruction from HE/RTL, whereas the other two test areas (2 and 3) had been repaired using like-for-like concrete to closely match the original concrete - as were most of the other patch repairs to the Bear Ravine.

*Corrosion Rate Measurements*- Corrosion rate measurements were taken of the embedded steel reinforcements within, and around, the four test areas in both the new and original concrete on the Bear Ravine. A schematic of the test areas at test sites 3 and 4 shows where the measurements were made, Figure 9.

Prior to the repairs being made, stainless steel threaded bars were attached (screw fitted) to the existing steel reinforcements. These <u>direct</u> electrical connections enabled both potential and corrosion rate measurements to be made (within the body of the concrete) after the repairs had been completed. A Linear Polarisation Resistance Measurement (LPRM) electrochemical monitor was used to take the NDT corrosion rate measurements on the repaired wall at the top of the bear ravine. The results are shown in Table 1.

**Table 1**

Corrosion Rate Measurements (µm/yr)

| Location | Area 1 | Area 2 |
|---|---|---|
| 1 Repair | 1.21 | 0.16 |
| 2 Left - original | 0.17 | 0.32 |
| 3 Right - original | 0.40 | 0.12 |

| Location | Area 3 | Area 4 |
|---|---|---|
| 1 back left on original | 0.31 | 0.17 |
| 2 back centre under repair | 0.31 | 0.40 |
| 3 back right on original | 0.27 | 0.22 |
| 4 top left on original | 0.50 | 1.06 |
| 5 top centre on repair | 0.65 | 1.32 |
| 6 top right on original | 1.46 | 0.98 |
| 7 front left on original | 0.80 | 0.53 |
| 8 front centre on repair | 1.20 | 0.28 |
| 9 front right on original | 0.91 | 0.54 |

These results are very similar to those found in previous assessments (2020, 2018 and 2017) and significantly lower (approximately 5 to 10 times) than those taken in 2016 soon after the repairs had been made. It is likely that the cleaned embedded steel rebars have now established a protective oxide film on the rebar surfaces (through the zinc painted layer). Note - corrosion rates below 5 micrometers/year (which they all are) are considered to be low. Note – 5 micrometers/year is 0.5mm in 100 years. Total corrosion loss in excess of 0.5mm would be required to delaminated concrete surfaces.

There does not appear to be any indication of ‘increased corrosion activity’ of the original concrete adjacent to the repairs, indicating that the ‘incipient anode effect’ is not affecting these repaired areas of concrete. This is probably to be expected as this type of deterioration has only ever been noted by the author where the concrete has been contaminated with chloride salts (marine or de-icing salts). However, a visual assessment of repairs 3 and 4 showed that the repair to area 4 showed significant cracking and shrinkage. This was obviously due to the repair material used for the patch; reported to have been made using a proprietary repair mortar. However, this could not be confirmed as its colour was similar to that of patch 3.

*Hammer Surveys* - Schmidt hammer testing was carried out on five typical repairs to the Bear Ravine. The average surface strength readings of the repairs were 36N/mm$^2$ whereas those of the adjacent parent concretes were 41N/mm$^2$. A concrete strength of 35 N/mm$^2$ is generally taken to differentiate between low and average quality concrete and above 50 N/mm$^2$ indicates high strength concrete. The surface strengths of both the parent and patch concretes may therefore be considered as of low average strength. When concrete is repaired it is a requirement that the repair concrete has similar strength to the parent concrete.

## 3. Site Visit (Meerkat Enclosure)

*Visual Assessments* – A visual assessment of the Meerkat enclosure showed no sign of any significant deterioration to any of the repairs, Figure 10. There were three very small areas of shrinkage cracking (<0.2mm wide) where repairs had been made to the fluted finishes to the low-level walls (due to too faster drying out of the repairs) but these were insignificant. The Meerkat enclosure was completed after the Bear Ravine in 2015, and it could be that the Dudley Zoo repair team improved their repair methods and application processes for this Tecton. Views of some of these repairs are shown in Figures 11 and 12 and they show that the repairs have now fully blending in with the parent concretes following seven years of weathering. The only other item to note is that there was a large area of the top counter which had been replaced and the top surface had been pre-weathered (brushed to remove some of the cementitious components and expose the rounded aggregate). When this had been carried out in 2015 the pre-weathered surface exactly matched the adjacent parent concrete which had been naturally weathered over 85 years. However, when it was examined in 2022 many of the small stone pebbles on the surface were now loose. This should be noted when pre-weathering to repairs is next carried out to future Tecton buildings.

The repairs were fully completed on this structure in early 2016. 4mm stainless steel threaded bars were mechanically attached to four of the existing steel reinforcements so that measurements could be taken both in the repaired areas and also on original concrete, Figure 13. An image taken of this area of the enclosure in 2022 is shown in Figure 14.

*Corrosion Rate Measurements-* Corrosion rate measurements were taken of the embedded steel reinforcements on the top surfaces which included the repairs, the parent concretes and also the interface (where the insipient anode effect may be operative). The results are given in Table 2.

**Table 2**

Corrosion Rate Measurements on Meerkat Enclosure (µm/yr)

| Location | Repair | Original | Interface |
|---|---|---|---|
| 1 Area 1 | 0.02 | 0.05 | 0.04 |
| 2 Area 2 | 0.48 | 0.56 | 0.29 |
| 3 Area 3 | 0.51 | 0.09 | 0.18 |
| 4 Area 4 | 0.55 | 0.09 | 0.16 |

Again, corrosion rates of all readings (repairs, original and interface) were lower than those measured in all previous visits. Some of this might reduction may be due to the drier concrete experienced in August (as compared to December 2020) but most is likely to be due to the steel having now developed a protective oxide film on its surfaces. There was no indication of 'increased corrosion activity' of the original concrete adjacent to the repairs, indicating that the 'incipient anode effect' is unlikely to be affecting these repaired areas.

*Hammer Surveys* - Schmidt hammer testing was carried out on five typical repairs to the Meerkat Enclosure. The average surface strength readings of the repairs were $31 N/mm^2$ whereas those of the adjacent parent concretes were $29 N/mm^2$. The surface strengths of both the parent and patch concretes may therefore be considered as of poor strength.

## 4. Discussion and Conclusions

The corrosion rates of the repaired concretes for both Tecton structures have now decreased significantly from those that were measured soon after the repairs had been completed. This is most probably a consequence of the formation of a protective oxide film on the steel reinforcements which passivates the steel surfaces.

The hardness values of the concrete in the repaired areas of both Tecton structures will now have reached their maximum values. This shows that both the parent and patch concretes are similar for both the Bear Ravine and the Meerkat Enclosure and there surface strength values are in the average to low range.

Visual assessments of the repairs have shown that there is now some cracking and shrinkage problems associated with the Bear Ravine; the other two Tecton structures (Kiosk and Meerkat Enclosure) appear to be almost free of all defects. These defects may have been due to problems when the Bear Ravine was repaired. The amount of damage to the RC on the Bear Ravine was considerable. The parapet wall (both to the ground and 1st floor) is thin and breaking out the concrete to get behind the steel (to fully clean it up) was always going to be difficult.

The corrosion rate monitoring of the repaired areas showed that all rates are now low and the data gave no indication that the incipient anode, or halo effect, was occurring. This is not particularly surprising since these concretes generally contain low levels of chlorides within their body and are not subject to either marine exposure or have de-icing salts deposited on their surfaces.

DZG have requested that a visual (NDT) defect assessment be carried out on all five repaired Tecton structures both to assess how the repairs are performing and also to inform future repairs to the other Tecton structures. This defect assessment is given separately.

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7th August 2022

Figure 1  View of the repaired Kiosk after 8 years exposure.

Figure 2  Fine crack leading out from the steel column, possibly due to differences in thermal expansion between the steel and the concrete.

Figure 3  View of the repaired Bear Ravine after 8 years exposure.

Figure 4  Cracks noted to the repaired parapet wall to the prow of the Bear Ravine. Note also the moss growth established in the fine shrinkage cracks to the upper balustrade rail.

Figure 5  Another crack noted to a repaired parapet wall to the Bear Ravine.

Figure 6  Classic shrinkage cracks noted around a square repair to the fluted section of the 1$^{st}$ floor wall.


Figure 7  View of the small patch repairs (1 and 2) on the outer wall at 1st floor level.  Patch 1 was made using a proprietary repair mortar and patch 2 was made using a like-for-like concrete repair.


Figure 8  View of the small patch repairs (3 and 4) on the inner wall at 1st floor level.  Patch 3 was reportedly made using a like-for-like concrete repair and patch 4 was made using a proprietary repair mortar .  Shrinkage and moss growth (in cracks) for patch 4.

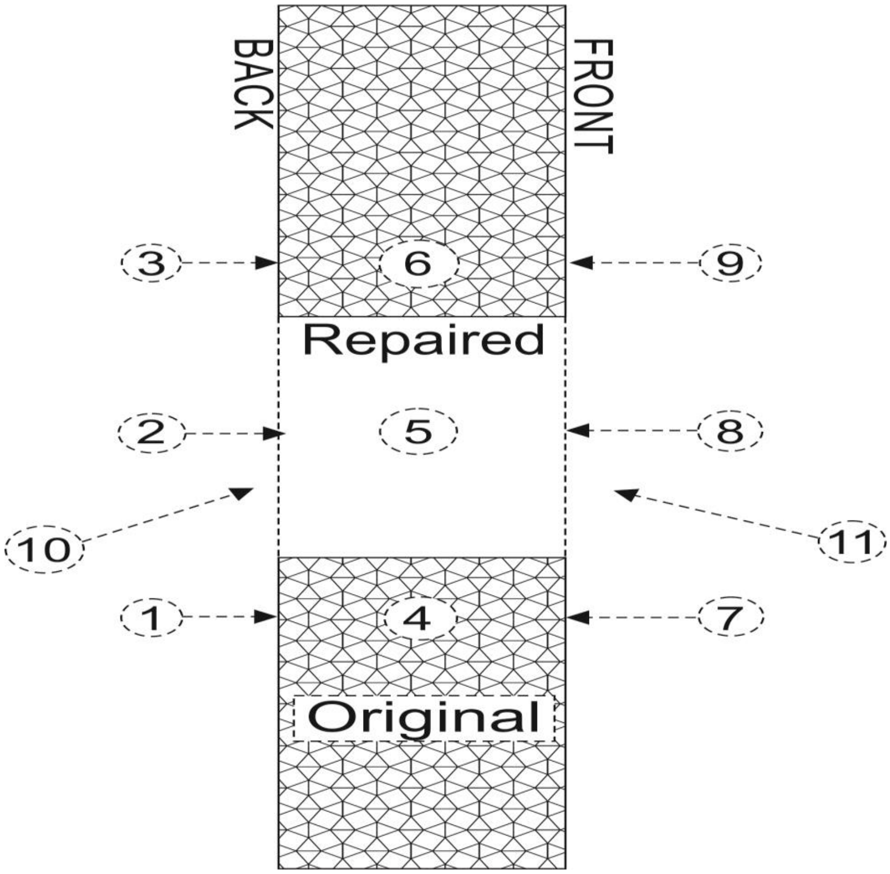


Figure 9 Locations where corrosion rate readings were taken in test areas 3 and 4 of the Bear Ravine 1st floor wall.

Figure 10 View of the repaired Meerkat Enclosure taken 7 years after completion.

Figure 11 The repairs to both the top section and vertical fluted section have now weathered and have blending in with the parent concrete.

Figure 12 Another view of a repaired section (horizontal and vertical) which has also blended in with the parent concrete.

Figure 13  Broken out section at the back of the Meerkat Enclosure (2015 - prior to repairs) showing the four stainless steel test points (right front and left back) attached to the different rebars.

Figure 14  View of the repaired top of the wall showing it fully blending in after 7 years exposure.