USE OF INTEGRATED SURVEY TECHNIQUES: MEASURING THE IRON BRIDGE

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Abstract. *The construction of a high parity 3d CAD model of the historic Ironbridge has demonstrated the value of integrating survey techniques to deliver spatial data of interest to historical analysts, conservators and presentation professionals. The performance of wireframe from photogrammetry as 3DCAD modelling source requires the use of infil techniques such as measured drawing, realtime CAD/REDM and laser scanning. The detailed survey needed to model the structure has added to the understanding of the manufacture and construction sequence.*

1 INTRODUCTION

The Iron Bridge at Coalbrookedale was scheduled as an Ancient Monument in 1934 and is the centrepiece of the World Heritage Site designated by UNESCO charter in 1986. The bridge is the world's earliest major iron span and is the prototype for iron bridge construction. It is uniquely important as the first structure to use iron at an industrial scale. The manufacture of the bridge components is a unique example of 18th century quality controlled production of structural iron. The bridge is constructed of large cast iron parts (the largest weighing up to 5.5tonnes) cast, positioned and fitted in 1779 under the direction of Abraham Darby III master iron founder and Thomas Gregory his pattern maker. The form of the bridge is derived from a design by Thomas Farnolls Pritchard, [i] the architect directed by the bridge commissioners in 1776. There is no surviving copy of Pritchard's drawing other than early scheme drawings for iron spans so it is an open question as to how much of the erected structure is from Pritchards design and how much is a result of foundry pattern work. [ii] The e historic central span of cast iron is of 30.12m. It is made up of 5 frames supporting a roadway of 42 cast deck-plates. The span is an arch of a near perfect semicircle standing on stone abutments. The deck rises at an angle of aprox. 5deg to a shallow arc joining the 2 pitched sides of the deck. In 1999 the bridge was found to be in need of painting as surface corrosion had become extensive and there had been some loss of the bearing between the deck-bearers and the deck requiring consolidation. [iii]

2 METRIC SURVEY REQUIREMENT

The proposed works needed metric survey drawings for scaffold design, marking up the painting regime and recording repairs. Metric survey was also used for the following purposes:

- The verification of historic photogrammetric survey from 1977, the previous survey was incomplete due to obscured areas in the photographs, the opportunity was taken to use the earlier work in the new survey;

- Data from archaeological investigation was plotted onto 1:50 ink on plastic photogrammetric plots to provide a precise base for the record of the type and phase of the bridge components in 2D.

- Acquiring a better understanding of the structure, there are many gaps in the knowledge of both the design and construction phases of the bridge, the 3D record enabled theories to be tested against true to scale information.

- The presentation of the monument to visitors with the use of 3D survey data in virtual and on site interpretation using high-resolution CAD models. Visitors should be able to observe the structure from viewpoints not possible in any other medium.

- Surveying in 3D enabled the twists caused by post erection deformation to be mapped, enabling stress analysis of the bridge and so failure mapping and prediction.

  The structure has undergone a number of movements since erection in 1779. The rotational thrust between the abutments and the pressure of the unconstrained stone work lead to a rebuild of the approach arches in 1821 and continued movement of the footings resulted in the below water ferro-concrete retaining work of 1972-3. The shape of the frames spanning the river has been distorted as a result of this and this needed to be recorded as a basis for monitoring and understanding future movement. A number of the original castings have cracked or snapped due to the above stresses. The failure and subsequent repair or replacement of components reveals much of the movement take up prior to 1973. The snapping of the radials on the S side of the span, the compression of the chords of the main ribs and the displacement and twist across the deck are all recorded to a consistent 3D positional precision of +/-25mm for the model and +/- 10mm in the photogrammetric wireframe.

- Recording the repair histories of the components in a 3D framework to enable the survey data to be used as a GIS for informing future projects

3. SURVEY TECHNIQUES

3.1. Control

A prerequisite of producing a complete survey of the bridge was the use of a common control. Thirteen stations were set out on an adjusted traverse. These were then used to ensure that the data produced by the different survey techniques was compatible. Control for photogrammetry required the stations to be occupied for the recording of 600 control points on the bridge. Observation was carried out by two-point intersection to detail points on the structure rather than marked targets.

3.2 Metric survey methods

The Iron Bridge presents a number of problems to the surveyor; the need for a wide range of scales from large [1:50] to small [full size], line of sight obstructions and access affected all the applied techniques. Lighting and vegetation were difficulties for photo-based techniques. When access was possible by scaffold instrument and hand survey techniques could be used, however gaps in the data set remained. Filling these gaps provided an opportunity to evaluate the performance of laser scanning, when applied to the rigorous levels of precision required to the survey of an historic structure of this kind.

3.3 Photogrammetry

Stereo-photography for photogrammetry was acquired from camera positions on the riverbank and also under the bridge at the footings, the photography was lit by available daylight. Vegetation obstructing sight lines from the riverbank and obscuring the retaining facades required the supplementary use of historic (1972) stereo-photography. The soffit of the span was obscure due to limited access, poor lighting and near camera obstructions. This resulted in a lack of cover of the soffit at the centre of the span. The camera used in both cases was a Wild P31 at a range of approx. 40m and the Ziess UMK 300mm for ranges exceeding 40m.

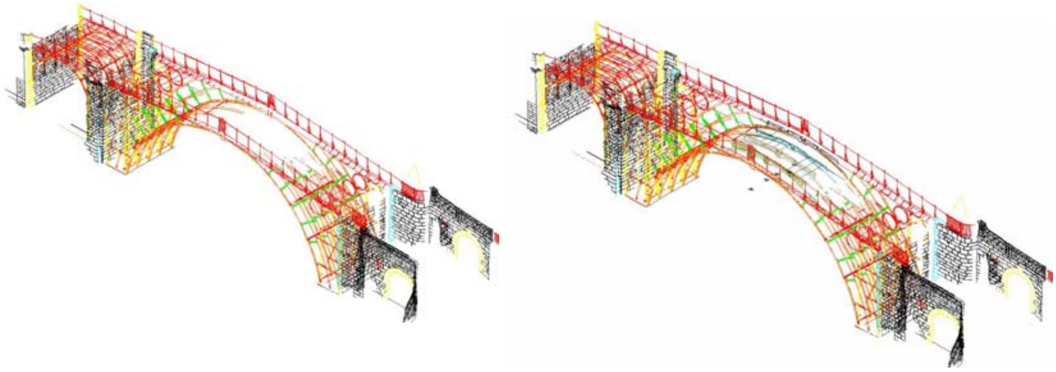

Figure 1: The wire-frame plotted from photogrammetry

The wire-frame is 3d but rarely plots all possible edges of components, this is due to line of sight obstructions, poorly lit imagery or indistinct edges. The consistency of precision in the wire-frame is an inherent property of photogrammetry. Note the soffit of the deck; there is little or no information here due to the deep shadow caused by exposure of photography for the outer frames of the span. (photogrammetric survey by PCA ltd)Right: The photogrammetric wire-frame completed by REDM.

3.4. Reflectorless EDM (REDM)

When access by scaffold was possible, REDM was used to in-fill gaps in the photogrammetric wire-frame. Stations were set up on the scaffold between each frame, and ties to the photogrammetric wire-frame were made by re-section to detail. By using instrument set-ups under the deck (figure 3) gaps could be in-filled at close range. All the REDM data was recorded in real-time into AutoCAD using TheoLt on a field computer, this process is manually operated 3d digitising. [iv]

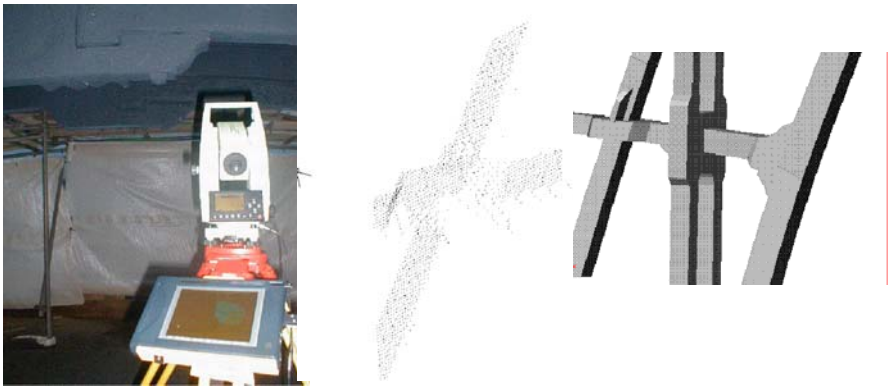

Figure 2:Infil survey techniques

Left: REDM set-up under the bridge deck tracing the crown bearer into AutoCAD using TheoLt on a field computer. Centre: the point cloud data from U K Robotics Z&F scanner: the points have failed to reveal any useful edge detail- some surface information may be useable prepared from point cloud. Right: modelling by primitive fitting to the point cloud. Because the point cloud is edge weak the modelling has failed to re-create the mouldings correctly

3.5 Narrative photography/site sketches

It was important to get a mix of both technical photography and images of a more observational style: the lighting used for one image may reveal aspects of the structure hidden by another: the tendency to take square on images for technical records use can produce a set of images with limited use. By getting photographs from surveyors, architects and archeologists an optimum mix was achieved: the tendency to take square on images for technical records use can produce a set of images with limited use. By getting photographs from surveyors, architects and archeologists an optimum mix was achieved.

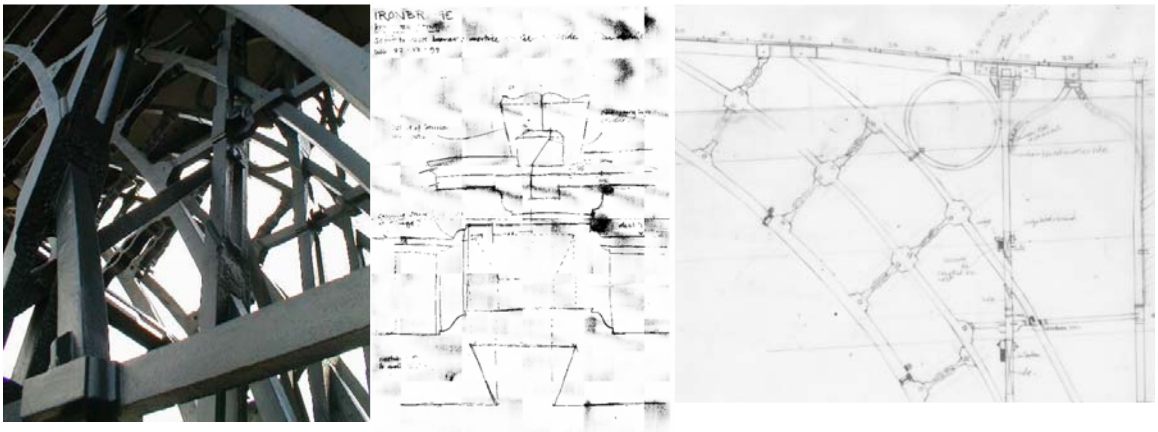

Figure 3:
Sketches and photographs prepared on site during inspection for the completion of the wire frame data.
The sketches show the method of inquiry: block diagram, component identification and hidden surface details. Right: Measured drawing prepared by Ironbridge Gorge Museum Trust Archaeology Unit: note the plotting of observations from detailed inspection

3.6 Laser scanning

Laser scans (see figure 2 centre and right) were taken to infill the deck soffit not mapped by REDM or photogrammetry. The data-cloud was modelled and prepared for insertion into CAD by use of automated surface extraction software. The laser scan was unable to supply any edge definition of components generated to the required tolerance due to the complexity of model and this is characteristic of data-cloud derived data. The main value of the data was to add to patches of information on surfaces between the wire-frame edges and to determine surface profiles of the lower parts of the main ribs. The data received from the laser scan was generally of poorer utility than that produced by photogrammetry.

3.7 Measured 2D drawing

2D details of the bridge's joints were recorded by on-site plotting of measured detail directly onto 1:50 scale elevational plots prepared from photogrammetry (see figure 3 right). Where needed control was by string levelled lines. The pencil annotations were then inked in. Ironbridge Gorge Museum Trust Archaeology under the direction of Shelly White.

4. CONSTRUCTING THE SOLID MODEL FROM THE WIRE-FRAME CAD MODEL.

Because the wire-frame from photogrammetry and REDM survey was built on a common control and CAD platform it could be used to form and fit solid components in true 3D positions. It was decided to use solid rather than surfaces modelling for the following reasons:

- Edge extraction; a solid model will allow the extraction of line drawings without disruption by surface meshes.
- File size is reduced compared to the surface model equivalent;
- Component fitting and counterpart modelling is possible using Boolean operands; the fit between parts can be used to create the edges of components.
- Element analysis is possible.

By building up closed regions from the wire-frame, solid parts were extruded into their true co-ordinate positions in space. Components were replicated and tested to fit the housings for the new position. Most of the joints have generous passing tolerances so it was surprising to find many parts could not be fitted in this way, most of the radial links between the ribs are one-offs suggesting that many castings were made to retro fit locations set during construction. The distortion of the main ribs is such that a reflection from one quadrant to its opposite is not possible. The simple arc sections used for the ribs are subject to tilt and twist and this needed careful interpolation of the wire-frame to develop solid components.

4.1. Modelling conventions and parameters

Modelling the bridge required a compromise between model integrity and CAD performance. The bridge comprises some 1420 cast parts (excluding fixings and fasteners): to model all the parts and their variants as full size replicas would generate a file size of approximately 500mb, unusable without extensive computer resources. It was decided that there should be a tolerance of up to 35mm surface to edge variation to economise on surface generation for the solids used. Where it can be inferred parts have a path through each other this has been interpolated in the model. Many joints are indistinct as they have been caulked with molten lead to fill voids and the internal spaces of the joint housings can only be estimated. As with simpler CAD models and drawings layering was used to separate the data by location, part name and phase.

5. INSIGHTS AND DISCOVERIES THROUGH METRIC SURVEY DATA

5.1. Evidence for the industrial process

The detailed examination required by the survey enabled the investigation of the manufacturing processes deployed on the structure. Two casting processes were used in the manufacture of the bridge components: First “Swept up” castings the mould is made in sand and left open to the air. Swept up castings are characterised by a pitted surface, particularly in the surface exposed to the air when the metal is poured.Second “Box castings” where the mould is closed by encasing the casting sand forming a closed void to be filled with molten metal. These castings have a smooth finish. Only 26% of the main castings were found to be from re-used patterns although the mortice boxes are re-used on the ribs. [A good example of this is the re-use in error of the mid rib mortice boxes on the upper ribs of frame C]. The fit of “cloned” parts in CAD indicated those parts probably cast from re-used moulds and inspection of photographic records confirmed this. Evidence for the casting processes used can be linked to the survey data. The characteristic pitting on the upcast surfaces of swept up castings can be applied to the CAD model using a bumpmap derived from photography. The variation in the sizes of the repeated parts was revealed by the 3D fitting of CAD replica parts to the wire-frame data at the model building phase. This variation from a standard pattern can be explained by:

- *The reuse of counterpart patterns for mortices and passing moulds*. The post assembly design, casting and fitting of components to fit tolerances derived from erection [eg the deck beams have a variable spacing of mortises]

- *The casting orientation and sequence*. It is noticeable that the upcast surfaces have been used for hidden faces of the structure where possible. There are some components that reuse a mould and the orientation of the mould can be determined by the upcast face [eg the diagonal ties are all the same part used in mirrored pairs]. It is possible to identify the extent of successful pattern fitting by fitting CAD model parts to wire-frame positions from photogrammetry and REDM.

- *Variation of pattern quality*. There is a noticeable grouping of components by quality of finish; the uppermost radials separating the ribs are of much poorer quality than those lower down. It is suggested that some components have been cast at speed from crude patterns to resolve critical erection problems. The wide spread use of open castings rather than closed also suggests an urgency to the component manufacture.

- *Use of retro fitted parts.* It is clear that the use of retro fitted parts was part of the construction sequence; the erection of a single frame requires the one off casting of at least 10 major parts out of approximately 40, to a fitting tolerances of +/- 25mm. The casting process from the fitting up of patterns, casting to fit at the tolerance required, oversize mould making and volatile material handling was probably unique to the Coalbrookdale foundries at the time.

5.2. Evidence for the development of fixing technologies;

It has been widely asserted (J.Dupre 1997, McGuire+Matthews 1958) that the structure relies on developments of the wood fixing technology of the day for the basis of its fitting and fixing of parts. This is not entirely so, there a number of fixings used that are unique to metal work.

- *Expanding soft iron wedge or plug*. This is unique to iron fixing and shows a highly developed understanding of friction behaviours in cast iron of different hardness.

- *Engineering technology.* Nut and bolts (square and hex) are used extensively for joints subject to twist (there are at least 229 C18th nut & bolt fixings used in the structure).

- *Blacksmith work.* Strap and band ties are shrunk to fit the 6 braces between the frames.

Some fixing methods are clearly derived from woodwork practice. Hidden halved dovetail, dovetail, mortice and tennon are all used, but using lugs, housings and the web closing mortises shaped to make best use of the superior strength to weight properties of cast-iron. If wooden components were of similar proportions the lug and web shapes would be much thicker.

5.3. Erection sequence.

A recent archive discovery (DeHaan /Skandia 1997) has indicated the erection sequence did not rely on massive timber false-work for the first ribs. Inspection of the crown joint for the survey (Blake 1999/2000) reveals a fixing system of some considerable complexity that supports the sequence suggested by Selby in 1999. The handling of the bridge materials is worthy of consideration, as the main castings were some of the largest cast objects on earth at the time.

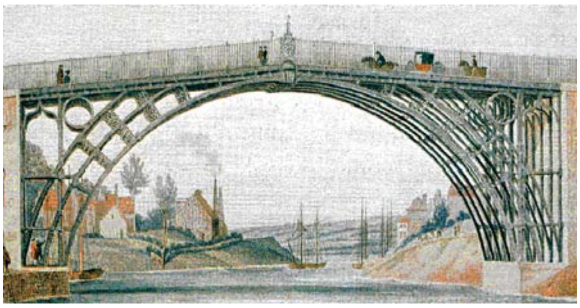

Figure 4

The view of the bridge by M.A.Rooker dated 1780 and the CAD model viewed from the same perspective centre: the “missing ribs” are shown although they were not in place until 1791 and the frame C casting error is absent; this then is a studio prepared view probably prepared from design drawings. The view of the CAD model matched to the view by M.A.Rooker-the view reveals the casting error on frame C.

Inspection of the bridge reveals that frame C [the central frame] differs from the others in 3 ways:

- No shoulder is cast into the outer vertical, the other frames all have this.The upper rib re-uses the 2 sided mortice mouldings from the mid-rib: this is a mistake as the mortices for the upper rib are only one sided. The error is not repeated on the other frames.
- The mid rib rests on a shoe fitted to the sole-plate all the other frames use a surface fixing detail.

The design modifications to the frames on either side of Frame C suggest some refinement of the parts took place during the construction phase and that Frame C was the first erected. The CAD model can be used to test erection theories. By fitting views of the model to the 1779 sketch by Elias Martin it is possible to re-create the sequence of assembly starting with frame C. Testing the fit of the parts by virtual assembly shows many of the displacements in the bridge may date from its erection. For example the cast size of the circles on the south side of the span are oversize to accommodate the cant on the inner verticals. This can be proved by bringing the verticals upright in CAD and testing the fit of the circles.

5.4. Assessment of pre photographic image/ drawing regression study,

Comparison with a matched perspective view by Rooker (c1782) reveals frame C details omitted adding to the evidence for this view being prepared from design drawings rather than from the structure itself

6. CONCLUSION

6.1 Survey Methods

Photogrammetry is the most reliable method for mass 3D data capture. However it can be compromised by the image quality of the stereo pair. The production of the wireframe used in the survey required detailed briefing of the contractor who was chosen on the basis of previous work of this kind. The selection of edges to produce a good 3D wire-frame for complex historic structures needs to be based on experience informed by a well founded architectural knowledge.The infill by REDM matched the wire-frame integrity from photogrammetry. Real-time CAD data collection allowed data selection and checking of a high order of precision and observational accuracy. The selection of targets was informed by real-time checking of the wire-frame on site. CAD is the optimum assembly platform for 3D data sets. The precision of the CAD environment matches that of the survey data and supplies the 3D tools for data completion using real-time CAD capture with TheoLt and measured drawing. Laser scanning did not supply good edge fitted modelling for the precision survey of the structure. The captured data from laser scanning is a data cloud: the selection of edges to form 3D positions from the cloud tends to lead to corruption of the delineation of the subject. This was exacerbated by automated feature extraction resulting in poorer data than from photogrammetry at the large [1:20-1:10] scales needed to replicate the engineered fit of the bridge components Opportunities for close inspection of the complex historic structures should be maximised and recorded by sketch and photograph. It was through careful inspection of the crown joint that the construction of joint was revealed. This evidence supported the reconstructed erection sequence. The next opportunity to inspect the joint may be 25 years away!

6.2 Verifying Historic Drawings

The works drawings for repairs carried out in 1902 and 1932 were made available to the project and it was found that the work carried out on the bridge differed from the drawings. Repair design drawings are useful but not as reliable as a 3D “as found” record.

6.3 The presentational use of the 3D CAD Model

The construction of a 3D model allows greater use of the survey data. The mechanical constraints of the bridge can be investigated, component integrity and failure patterns tested. The 3D model also has a great presentation potential for such a well visited site. It can be used for virtual reconstruction, construction animations, showing historic ad-hoc design indications and explaining the conservation and analytical work undertaken.

6.4 Acknowledgements to an Interdisciplinary team

The exchange of information between specialists has enabled the recording process to produce enhanced 3D products. The Metric Survey and CAD assembly was undertaken by the English Heritage Metric Survey Team, and a detailed record based on 2D photogrammetric plots and narrative photography prepared by the Ironbridge Gorge Museum Trust (directed by David de Haan). Archeology by Shelly White IGMT enabled the infill of the 3D wire-frame by supplying 2d record drawing for digitising. Type specific knowledge is vital to specialist recording, the recording of variation in components, their displacement etc should be informed by a knowledge of the design constraints, methods used and known repair regimes. David De Haan of the Ironbridge institute made available his in-depth knowledge of the history of the bridge to the project and this focused the survey work on specific details and areas. It also informed the later animated construction sequence produced from the 3D model.

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