Rebuilding Woolwich Arsenal Clock Tower

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There are few things more likely to create a hush around a structural engineering office than the words “there has been a collapse on site.”

On the 23rd of October 2008 The Warren Development at Woolwich Arsenal was 90% complete. A £77 million redevelopment project involving the adaption and preservation of historic military ranges and two, new build, seven storey RC residential blocks to modern design. Then the call came through from the contractor – the north range clock tower had collapsed.

Even without any witness accounts, arriving on site it was hard to avoid the obvious conclusions as to the root cause.

The specifics behind the collapse are not the subject of this paper. Rather to demonstrate that the success of heritage forensic engineering is intrinsically linked to adhering to the conservation principles as laid down in the Australia ICOMOS Burra Charter, 1999. The Venice Charter and English Heritage Conservation Principles.

However, in order to understand the full scope of issues that faced Conservators and Structural Engineers the following series of events were relayed.

The grade II listed 19th Century clock tower consisted of a 3m high louvered timber bell tower with lead cupola sitting on twin timber king post trusses. These trusses also supported root purlins and sat on the load bearing masonry walls. The rear wall having recently been rebuilt with the arch formed via a concrete frame. A temporary tie rod was still in place when an unauthorised large earth mover attempted to traverse from one side of the range to the other.

The arm of the digger collided with the tie rod, pushing the arch from its bearings. With the arch removed the truss bearings dropped and the rest of the clock tower along with them.
Immediate action

Safety of course was the immediate concern and remained the top priority; thankfully no-one had been injured in the collapse. Even at a distance it was apparent that the collapse had the potential for further failure and significant instability remained. The area around the collapse was cordoned off whilst engineers assessed what had happened as best they could from neighbouring buildings in safe proximity.

In the first instance the Northern bearings to the twin trusses remained in place acting as the pivot point as the southern bearings dropped away with the arch.

The trusses straddled the digger with main carcass of the clock tower striking the cab and the extended arm. The impact shattered three of the louvered sides of the bell tower, but crucially one of the sides remained largely intact. The lead cupola was also seemingly unscathed, albeit that the connections to the surrounding framework were now ruined under the impact of its considerable weight.

The twin trusses not only supported the clock tower but also the purlins spanning to the adjacent trusses. Had the purlins being configured as 'butt purlins' they would have allowed the two adjacent trusses to collapse. As it was the 'through purlins' now cantilevered from the intact sections of the roof providing the only means of support to the adjacent trusses which now seemed very precarious.

The weight of the collapsed clock tower was now partially supported on the digger and part on the twin trusses, which now leaned against the inside face of the front wall. The southern rear wall was pretty much demolished down to the stone band course and the bulls eye windows were also corbelling in a precarious state.

Immediate action items were drawn up and issued, principally focusing on safety concerns. No access whatsoever was allowed to the immediate area both internally and surrounding the building. Whilst time was of the essence it was clear that the rigours of fact finding, assessment, testing, analysis and interrogation were going to be crucial in establishing effective remedial proposals. These proposals had to be cost effective, time efficient, appropriate to the scheme and, not least, heritage sensitive.
Information gathering / assessment

As the engineers involved in the original proposals for adaption Ramboll had already accumulated significant amount of information on the Clocktower to assess and preserve the heritage. [Principle 3: Understanding the significance of places is vital][3] Desk top research by engineers and the architect had been conducted and backed up by extensive site investigation. Through the first phase of the work this understanding of the structural form was employed in assessing the state of the collapse.

Records indicated that the evolution of the structural form centred around its semi-industrial development as the Royal Arsenal from 1805. Solid load-bearing masonry with lime mortar and heavy timber king post trusses had been recorded as surviving the ravages of time reasonably well. Some remediation had been required where water ingress had caused damage to truss bearings in valley gutters. Restricted access and the sheer bulk of these timbers resulted in whole scale intrusive remediation being unwarranted. [6.1 the cultural significance of the place and other issues affecting its future are best understood by a sequence of collecting and analysing information before making decisions. understanding cultural significance comes first then development of policy and finally management of the place in accordance with the policy.][1]

At the time of the collapse the clock tower area of the site was in the process of being adapted to become the principle entrance to the development when approaching from the river. Several heritage features had been reclaimed from other areas of the site for reuse in this entrance, including cast iron columns and riveted steel beams. Significantly these riveted steel beams were to be employed structurally and had been established on their bearings prior to collapse and were still in place.

Whilst the pre-collapse structural form could have been described as ‘robust’ it was clearly now in a perilous state.

As soon as it was viable suspended access was arranged via man-basket from a mobile crane to further assess the damage and stability of the precarious elements as close as safely possible. It was evident that small-scale instability of tiles and broken timbers posed a threat to any operatives approaching the building on foot.

Figure 6 – view from man-basket

It was clear in the immediate days after the collapse that some significant elements of the wreckage were still ‘on the move’. As can be seen here from Figure 7, taken two days apart, the lead cupola is still slipping down the arm of the digger. Not only a hazard to anybody approaching the wreckage, this significant heritage feature appeared to have weathered the collapse largely intact and was in danger of falling further and becoming damaged beyond recovery.

Figure 7 – Cupola slippage within the first 4 days
It was imperative that primary support was installed to prevent total loss of significant heritage elements. However, before this could happen the small unstable ancillary elements of tiles, timber and battens were either established as stable or made to fall by testing with a bar from operatives suspended in the man basket above the debris.

In the meantime temporary shoring proposals to the front wall were established with the demolition contractor Keltbray. The principle being that two lightweight scaffold towers would be constructed remotely and manoeuvred into position prior to the kentledge being installed.

**Interrogation of information**

At the time the Woolwich Arsenal contained several disused engineering workshops which were already employed as storage for some of the salvaged historic beams and columns reclaimed from elsewhere on the site.

Recording the disposition of the elements amongst the wreckage, careful deconstruction of the collapsed structure now took place. The workshops now served as layout and storage space for the retrieved sections of the clocktower.

Piece by piece individual elements were mapped and assessed. Working with the record information and photographs from the original survey individual elements were identified and painstakingly recorded by the architect, AQP. This enabled the construction of a 3-dimensional computer model of the superstructure of the clocktower. Timber experts Hutton and Rostron were appointed to survey the salvaged timber for damage and extent of rot.

The entire design team, including the contractor, gathered to review the information in consultation with English Heritage. [122- intervention demands: a skilled team, with the resources to implement a project design based on explicit research objectives][3] The significance of the clock tower within the development and surrounding community had already been established. Fortunately the internal workings of the clock had mercifully been transported away for restoration at the time of the collapse. Further demolition and rebuilding, whilst potentially the most expedient solution, was universally rejected in favour of restoration. [2.1 places of cultural significance should be conserved.][1]. The strategy devised was to maximise the salvage of recoverable material. The question now was what was realistically recoverable?
In some small way the collapse had afforded the team an opportunity that would not have otherwise been available. The complete deconstruction of the clock tower timber carcassing allowed access to areas of the super-structure previously not viable.

Lack of maintenance and some poor weathering details were the likely culprits in much of the rotten bearings and walls plates. Whilst these had partly been addressed in the previous small-scale remediation, the team were now in a position to fully assess these otherwise hidden issues.

Other than the bearings, the primary trusses themselves were largely free from rot; another exception being where water had gathered at the junction of the central hanger to the principle tie member.

Figure 10 – Tie rot

It was apparent that the primary structural twin king post trusses had suffered under the impact loading of the collapse. The principle rafters had split in at least one place and wrought iron strapping had broken. The internal integrity of the connections was now questionable. There was no way to inspect these joints internally without destroying the integrity of the connection that was trying to be proved. Were this a new build there would be strong financial arguments for the existing timber to be abandoned and a new timber roof designed as a replacement.

However as with all historic structures it is necessary to let the building dictate its own constraints and abilities. The bespoke nature of the original clock tower, from a heritage perspective and from dimensional distortion, merited further investigation of the capacity of the trusses. The existing timbers were seasoned and had found their level with the surrounding structure before the collapse. Any new timber structure would struggle to match the unmolested strength and the dimensional constraints. The conservation argument was reinforced with a sound financial argument for re-proving the trusses.

Exploiting every available technique

In order to fully assess the potential for reuse it first need to be understood how these trusses were loaded and would be again. Using the 3D computer model, formulated from the historic information and detailed mapping of the salvaged timber, we were able to accurately assess the load paths through the intended reused and replacement clocktower super-structure elements. {4.1 Conservation should make use of all the knowledge, skills and disciplines which can contribute to the study and care of the place.}[1]

During the successful recovery of the cupola a relatively accurate assessment of its weight was recorded at 30kN. This was provided via the load gauge on the mobile crane which arrested the slipping cupola. This combined with the previous survey information and measurements of elements laid out in the workshops, allowed an accurate load assessment of what would be applied to the trusses under dead loading conditions. Standard live load theoretical analysis completed the model.

Figure 11 – 3D salvage & replacement

As anyone dealing with Heritage elements knows they often don’t bear analytical scrutiny. However but the model was primarily formulated to provide member forces for the design of the repairs, the rest of the undamaged structure being seen to have proved itself over time. Also the trusses supported an array of transfer beams and posts that formed the carcass of a clock tower. The arrangement of
spreader and props didn't necessarily coordinate with the internal members of the truss and most of the primaries were also acting in flexure.

Not only did the model give an accurate assessment of the design parameters for the repair sections, crucially defections were allowed to be predicted under different loading conditions. This was particularly important in the next phase full-scale load testing.

**Proof of the pudding**

However another factor loomed on the horizon. The main Warren Development was largely complete at the time of the collapse, one of the last elements being the testing of the drainage serving hundreds of dwellings. Unfortunately the main connection to the adopted sewer via a 325mm diameter pipe was intended to pass directly between the arches of the clock tower. All the infrastructure had been in place prior to the collapse other than the final drain run.

Even with all the trusses, carassing and remaining clocktower elements in storage and the digger removed, a large amount of kentledge supported the facade retention and sat directly on the route of the trench.

With dozens of families expected to move in by March 2009 having signed contracts, this element of work was now critical. Various heading options were considered along with phased removal of the kentledge. However it was finally decided that Ramboll's option of supporting the front wall via an internal 'flying' set of temporary steelwork was the most appropriate to free up the site in the safest and fastest manner.

Figure 12 – Temporary works and kentledge

Prior to the collapse two heavy riveted steel beams had been reclaimed from another part of the site for reuse as structural elements. These remained in place and an assessment of the structure demonstrated that the damage was almost entirely above the line of these beams which were now significantly assisting the stability of the front wall.

The design consisted of a series of 'push/pull' raking stays supporting the walers sandwiching the facade. These raking stays terminated at a line of beams supported off the heavy riveted steel beams. Lateral forces were resolved through bracing fixed back to undisturbed shear walls flanking the clock tower.

At the highest points of the pediment the external waling restraints were fixed via 600mm long 8mm diameter threaded bars. These were carefully positioned by drilling externally through the mortar bed joint so as to avoid disruption of the historic brickwork.

\{ 11c.The proposals are designed to avoid or minimise harm, if actions necessary to sustain particular heritage values tend to conflict.\}[3]

Figure 13 – push / pull raking stays

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Towards the lower levels ties passed through the bull's-eye windows and arched entrance to avoid even this low-level intrusion. By using a series of CHS struts between the walers sufficient distance was maintained from the facade to avoid damage of fenestration details; the final restraint interface being via folded timber wedges.

The internal position of the raking stays was carefully coordinated to ensure that the installation of the permanent works could be executed without adjustment of the temporary restraint.

To avoid drilling the exposed flanges of the reclaimed beams large Lyndapter connectors were employed at the junction with the bracing beams.

As well as releasing the kentledge and allowing freedom of movement around the clock tower ground floor this arrangement of ‘flying’ temporary works most crucially allowed the installation of the drainage connection via traditional trenching methods whilst ensuring the stability of the original fabric.

Running in parallel with this operation the principle truss repairs had now taken place. Rotten timber had been cut out and, where substantial integrity had been lost, additional steel plating with replacement infill timber had been introduced. This effectively replaced the action of the original unimpaired timber member. {118. While sufficient work should be undertaken to achieve a lasting repair, the extent of the repair should normally be limited to what is reasonably necessary to make failing elements sound and capable of continuing to fulfil their intended functions.}[3]
The splint repairs at the breaks in the primary rafters were carried out with steel plates and single sided shear plate connectors. Whilst the integrity of the original handmade bolts was unknown they were given the benefit of the doubt as being structurally sound, as well as contributing significantly to the character of the trusses. Consequently templates were crafted prior to fabrication of the steel plates to ensure that the handmade bolts remained undisturbed. [3.1 conservation is based on a respect for the existing fabric, use, associations and meanings. It requires a cautious approach of changing as much as necessary but as little as possible.][1]

With all of the repairs completed the timber trusses were placed in temporary testing rigs. The primary loads supported by the twin timber trusses had been assessed as being transferred via the sizeable (300mm x 300mm) timber bulks supported from the main tie members.

In consultation with the testing engineers (Train & Kemp) it was decided that the load that would be applied at the purlin positions would be static and the incremental load would be applied where the bulk timbers met the principle trust tie.

Figure 18 – historic fixings preserved

{120 The use of original materials and techniques for repair can sometimes destroy more of the original fabric, and any decoration it carries, than the introduction of reinforcing or superficially protective modern materials. These may offer the optimum conservation solution if they allow more significant original fabric to be retained.}[3]

Strain gauges were positioned beneath the tie members as the load was applied incrementally and the figures compared with the theoretical finite element model. If at any time the gauges exceeded 20% of the theoretical values or the reading failed to come to rest, the load would be removed. The truss was loaded at 5kN intervals to 110% of its theoretical maximum loading and passed all of its criteria. The predicted deflections of 5mm under full dead load were measured as 3mm in the test rig.

Figure 19 – full load test

{ARTICLE 10. Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.}[2]

Concurrently with the full-scale load test of the trusses conservation and materials experts, Carrig UK, were employed to assess the suitability for reuse of the existing lead cupola. With careful repairs this was deemed worthy of reinstatement.

With the principle heritage members having proved themselves fit for reuse there now remained the task of reestablishment into the rebuilt and re-stabilised load-bearing masonry of the clocktower.

The front face of the pediment superficially appeared unscathed from the collapse. Certainly the damage seemed minor in comparison with the substantial amounts of masonry lost around the truss bearings internally and the bulging brickwork beneath the coping stones. However, the pediment was now some 50mm out of plumb leaning inwards, there was 2mm to 5mm horizontal and diagonal cracking where the pediment had translated 25mm inwards. The bulging brickwork had been removed
and re-used in the reinstatement in matched lime mortar. The repairs around the truss bearings in the front wall were adjusted from the original removing detailing weakness and allowing for a 25mm air gap around the sides of the timber bearing. (119 Once failure occurs, stabilising the structure depends on addressing the underlying causes of the problem, not perpetuating inherent faults.) [3] Each bearing had four course engineering brickwork padstones. The design of the rear wall reinforced concrete arch remained the same as was previously constructed. The remainder of the reinstatement was completed in reclaimed brickwork forming pockets to accept the truss bearings.

As the 2½ tonne trusses were being lifted into place the careful planning of the temporary works proved its worth as the trusses swung into position unhindered. The line and levelling operation would have been much more complex had new timber trusses been fabricated. The original structure that remained provided fixed positions in relation to members that had deflected through the course of time. 'Straight and true' they may have been at one time following the original construction, but the rebuild was now marrying in members that had been reused, deflected, subject to rot, catastrophic failure, repairs and now reinstatement with additional members.

Figure 20 - bearing reinstatement

The success of this operation was dependent on flexibility. Not only in the position of the members but in the ability of the detailing to be crafted to suit the site constraints. In this timber and traditional detailing proved itself the most malleable. The high strength steel plating repairs had been detailed with sufficient tolerance to allow the original timber to timber connections at the seating of the through purlins against the principle rafter to be crafted traditionally. (4.2 Traditional techniques and materials are preferred for the conservation of significant fabric. In some circumstances modern techniques and materials which offer a substantial conservation benefits may be appropriate.)[1]

The original pediment was not connected to the timber framework other than at the truss bearing positions. During the collapse the pediment had moved out of plumb and fractured. Whilst some of the integrity of the pediment was restored with stitching of the principle cracks, it still remained significantly out of plumb.

Investigation of the walls makeup and subsequent calculations suggested that it was prudent to employ a series of strap restraints at noggin positions between the pitched rafters at the rear of the pediment. The visible impact of these was minimised by installing them in advance of the timber rafters.

The approach taken with the timber was to reinstate as much as salvageable and, where this could not be achieved, replace with matched timber where required. The salvaged complete face of the bell tower proved an essential template in crafting the three other sides that had been destroyed. In part the successful marriage between new and old was in being honest. Not trying to disguise the new elements but to celebrate the traditional detailing.

Similarly no attempt was made to try to disguise any of the steel repairs as being contemporary with the original. Modern bolts and strapping were finished with the same black paint as the rest of the metal work but remained distinct. The reclaimed steel beams were similarly finished and augmented with reclaimed columns to create a colonnade entrance beneath the clocktower.

Figure 21 – reclaimed sections new plinths
The reclaimed columns, themselves easily capable of supporting the floor and wall loads, were in fact made non-structural by a hidden movement joint. The reason for this was the ground conditions were so poor, consisting of variable made ground encountered to a depth beyond 2m. The shallow pad foundations had such low bearing capacity (40 kN/m² from plate tests) that any load attraction from the floor had the potential of causing small settlements which in themselves would have little structural impact but still cause disruption to the stone plinth and so deemed unacceptable. This allowed reinstatement of the columns that expressed the vernacular of the arsenal to be reinstated in a position which both served to reinforce the importance of the clock tower and salvage these heritage features in a sympathetic context. \[9.3\text{ if any building, work or other component is moved, it should be moved to an appropriate location and given an appropriate use. Such action should not be to the detriment of any place of cultural significance.}\][1]

Now all that remained was the reintroduction of the clock itself. Mercifully at the time of the collapse the mechanism of the clocktower and clock faces had been removed for repair and refurbishment. Much of the original plinth on which the clock mechanism sat was able to be reclaimed and reinstated.

All told when the repairs were finally complete more than 85% of the original timber was reused and cost less than £350,000. Such was the success of the detailing between the historic and new elements that the superstructure in this relatively small aspect of the Warren Development is expressed and celebrated as one of the jewels in this project. \[14c.\text{ The proposals aspire to a quality of design and execution which}\]

It is the efforts made in the application of heritage best practice that should be acknowledged here. Conservation principles are established to allow heritage practitioners access to the most appropriate measures to ensure survival of the cultural value of a place. Using the opportunity the collapse presented to apply forensic engineering to the potential weak points in the heritage structure has helped to ensure its survival. The dedication by the contractors and design team to maximise the conservation, using traditional techniques and materials alongside modern methodology and appropriate interventions in no small measure contributed to this being shortlisted for the Institution of Civil Engineers 2011 London Heritage Award.

References: