

Evening Meeting

An invited paper, presented and discussed at a meeting of the Institution of Structural Engineers, 11, Upper Belgrave St, London SW1, on Thursday, 18 October 2001 at 6pm.

Kingston Bridge strengthening – Phase 1

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Synopsis

Kingston Bridge carries the M8 motorway across the River Clyde to the west of the city of Glasgow. It is a strategically important bridge providing the primary crossing of the Clyde within both the regional and local traffic networks. This paper describes the development and implementation of the £30m strengthening contract undertaken by Glasgow City Council for the Scottish Executive between 1996 and 2001 to rectify significant defects. The paper also includes a description of the defects, the bridge assessment findings and the strengthening and repair techniques employed in the works. Finally, there is a description of the management of the bridge to maintain its operational condition throughout the project.

Introduction

Kingston Bridge carries the M8 motorway over the River Clyde in Glasgow. Opened in 1970, it consists of a pair of three span bridges carrying five lanes of traffic in each direction. It was constructed in balanced cantilever (a paper describing the construction of the bridge was published in *The Structural Engineer* in 1971¹). The bridge is currently carrying 180 000 vehicles per day.

Piled foundations were constructed behind the quay walls and hammerheads were built on both sides of the river. Voided deck panels were then constructed alternatively on the landward and riverward sides and post-tensioned back to the hammer head. This continued until the landward spans were landed at half joints on the previously constructed approach structures. Construction then continued out across the river and an *in situ* concrete closing panel then joined the two halves of the bridge together. The two halves of the deck were then post-tensioned through the closing panel and the two bridges were also post-tensioned together at quarter point diaphragms. Finally, the pin bearings at the top and bot-

tom of the North Piers and at the bottom of the South Piers, which had been locked up during construction, were released.

The articulation of the bridge as constructed is shown in Fig 1.

Bridge inspections

In the late 1980s inspections of the bridge began to show that it was not behaving as the designers had intended. Expansion joints at the North Half Joint where most of the bridge expansion should have taken place appeared to be permanently closed and did not move with the seasonal cycles. The expansion joint at the south side of the bridge was moving but was excessively open, especially in winter.

Surveys of the North Pier, which was pinned top and bottom, showed that it had developed a lean to the north which was causing the curtain walls around the lower bearing chamber to crush. Surveys of the deck profile showed that a dip had occurred at mid-span which was 300mm below the as-constructed profile and inspections of the soffit of the deck below the dip revealed cracks that were up to 2mm wide.

Bridge monitoring

A bridge monitoring system was installed on the structure to try to understand how it was actually behaving. Temperature sensors were installed at various levels in the concrete and movement sensors were installed around the bearings and at the expansion joints.

Interpretation of the monitoring data showed that the relaxation of the prestress due to creep and shrinkage had caused the dip at mid-span and due to the asymmetric nature of the articulation this had caused a sway to the north. The sway had caused the lean of the north pier that in turn had caused the upper rocker bearing to slip. The sway had also caused the north expansion joint to close and the bridge expansion was being accommodated by the bridge pushing the approach structures to the north in summer.

Bridge assessment

Calculations were carried out which checked the bridge for the observed defects and also included the necessary checks for the introduction of the 40t vehicle assessment loading. These calculations identified that if maximum loading occurred on the main span while the end spans were unloaded then the main span would become overstressed and uplift of the end spans would occur which could lead to the formation of a mechanism and a potential sudden bridge collapse.

Design checks on the main bridge piers showed them to be significantly overloaded and design checks on the foundations showed that the pile cap was unable to carry the knife edge loading being transmitted through the line of lower pin bearings.

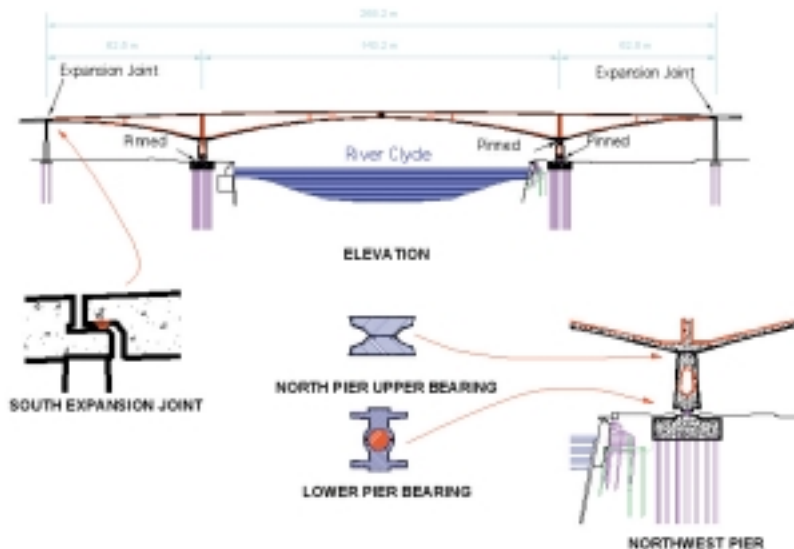
Interim measures

Until the strengthening works could be carried out, interim measures had to be implemented to prevent the bridge from becoming overloaded. This was achieved by a combination of reducing the number of running lanes on each carriageway

Keywords

Bridges, strengthening, heavy lifting, prestressing, retrofit, jacking

Fig 1. The articulation of the bridge as constructed



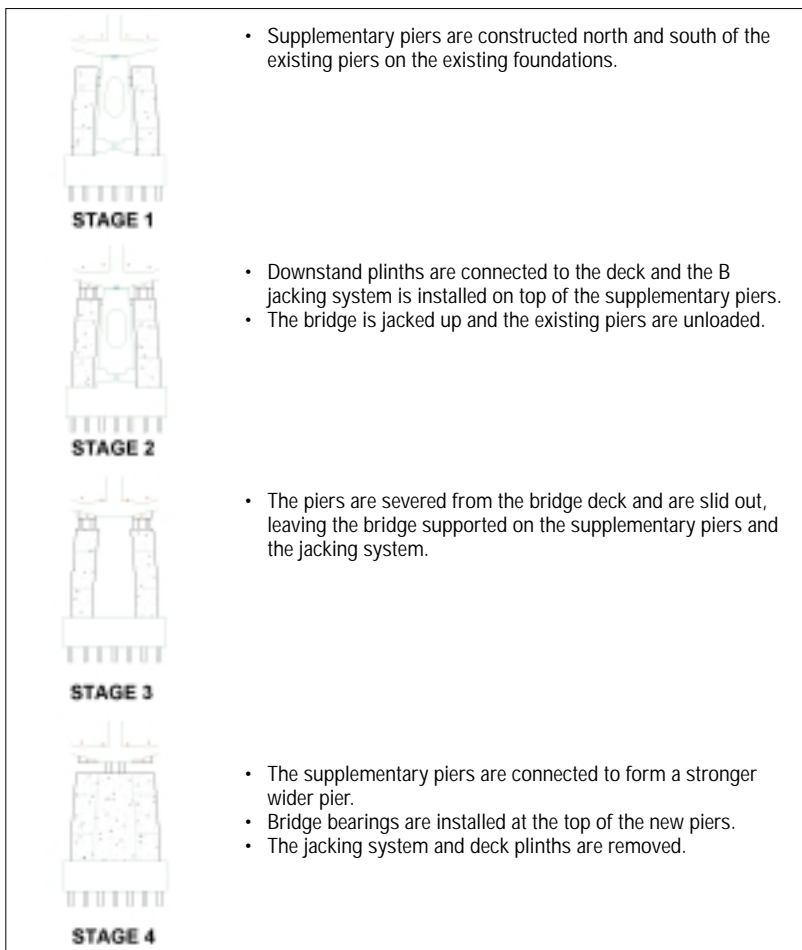


Fig. 2. Methodology for demolition and reconstruction of the bridge piers

Fig. 3. Lane restrictions and concrete blocks during the works



on the bridge from five to four, weight restricting one of the lanes to 7.5t, and placing concrete blocks at the end of the bridge to increase end bearing reaction.

Design of the strengthening works

A project design team was set up within the Roads Design section of Strathclyde Regional Council which was responsible for the bridge at that time. A contractor (Balvac Whitley Moran), a firm of Consulting Engineers (Gifford) and a European prestressing manufacturer (VSL) were invited to join the design team and assist in designing a strengthening scheme for the bridge.

The strengthening scheme which was finally chosen had four distinct phases:

1. Deck strengthening by the application of external prestress
2. Demolition and reconstruction of the bridge piers while supporting the bridge deck on a jacking system
3. Repositioning of the deck in an optimum position by horizontal jacking
4. Installation of the new bridge bearings.

The contract to carry out the strengthening works, which was chosen for its quality and cost criteria, was awarded to Balfour Beatty as main contractor with Balvac Whitley Moran as specialist subcontractor for prestressing and VSL (France) as specialist subcontractor for jacking. The contract was awarded using the New Engineering Contract, Engineering and Construction Contract option C Target contract with activity Schedule.

Deck strengthening by the application of external prestress

The bridge deck strengthening works comprised of:

- The installation of concrete anchor blocks in the end spans connected to the existing webs and bottom slab by post-tensioning bars.
- The installation of deviators at existing deck diaphragms.
- Threading post-tensioning cables from the south side of the bridge to create 20 No. 12 strand web tendons and six No. 48 strand bottom slab tendons per bridge.



Fig. 4. External prestressing tendons retrofitted inside the existing bridge deck voids

These tendons, which were external to the concrete section but located inside the deck void (Fig 4), were then stressed incrementally from alternative ends of the bridge, using three or four single strand jacks. A strict simultaneous stressing sequence ensured an even rate of stress application and also ensured that no torsions were induced in the webs.

Approximately 90MN of additional prestress was induced into each deck. To ensure strand replaceability, the strands, which are greased sheath monostrand, were kept parallel along the whole length of the tendon and grouted after stressing. Strand replaceability trials were carried out after grouting to demonstrate that replaceability had been achieved.

Demolition and reconstruction of the bridge piers while supporting the bridge deck on a jacking system

The demolition and reconstruction of the bridge piers was carried out whilst the bridge was still open to traffic. A methodology is shown in Fig. 2.

Bridge jacking systems

A key feature of the project was a sophisticated, state-of-the-art jacking system, required to lift, support and move the 52 000t deck to facilitate the works. The contractor was responsible for the development and design of the system and computerised jacking control system. In order to maintain free articulation, the jacking system could not be 'locked off' and the decks were supported on 'live' hydraulics for a period of 10 months while the bridge remained opened to traffic. Displacement measurement accuracy of 0.1mm was required so that the control system could control the jacking positions to a tolerance of 1mm during the jacking operations. Complex failsafe provisions were also required.

The jacking system which was used to lift the bridge and unload the existing substructure comprised of four separate jacking systems, A, B, C and D. Each was operated and



monitored by a computerised control system.

The B system was used to lift the bridge and support it on hydraulics for a period of 10 months. It comprised a system of 128 1000t jacks which were supported on new columns and reacted against downstand plinths connected to the deck. The B System consisted of 32 active jacks per pier which were capable of lifting the bridge but because the bridge would be supported on hydraulics for such a long time, this was backed up by 32 reserve jacks in case the active system failed. Each jack was equipped with a locking collar as an ultimate rigid support in case of failure of both the active and reserve systems. All B jacks were capped by sliding and rotating devices to permit horizontal and rotational movement.

The A, C and D systems were horizontal systems that provided the longitudinal and transverse fixity of the bridge deck when it was supported by the B system. The C system was also used to move the bridge deck to the south to relieve the load on the north approaches and to partially redress the excess travel on the south bearings (Fig 5).

Prior to bringing the system to site a very sophisticated sequence of factory acceptance tests was carried out to demonstrate that the jacking system would comply (under all circumstances) with the specified position and load control criteria.

During a 17h total closure of the motorway, which took place in October 1999, the 52 000t bridge deck was lifted 20mm. One week later during another overnight closure the deck was pushed south 30mm (Fig 6).

The B system jacks were hydraulically linked to effectively provide a two point vertical support. The control system was required to provide extremely tight controls and checks on both position and pressure. After the bridge had been lifted and moved, the jacking control system was placed in maintenance mode. In this mode, the bridge position and pressure status of the complete hydraulics system were continuously monitored by the computer controlled jacking control system while the demolition and reconstruction of the new piers took place.



Fig 5. Hydraulic jacking systems B and C



Fig 7. Existing pier slid out from below bridge

Traffic management

A requirement of the contract was that certain activities could only be carried out with the bridge totally closed to traffic. Analysis of the traffic flows had identified that the lowest flows occurred during a 17h period from 7 pm on a Saturday night to mid-day on a Sunday. The contractor had to state in his tender how many of these major closures he would require.

To accommodate the displaced traffic during closures, 11 diversion routes were set up, carried out with the co-operation of five adjacent councils. It was the largest traffic management system seen in Scotland. The closures were accompanied by a publicity campaign in the newspapers and on radio to advise the travelling public when the closures would be and what diversion route would be most suitable for their journey. The diversion routes were monitored during the bridge closures from the National Driver Information and Control System (NADICS) in Glasgow.

Pier slide out

Once the pier had been severed from the bridge deck the existing pier had to be slid out from below the bridge and leave it supported by the supplementary piers and the jacking system (Fig 7). This was envisaged at the tender stage as being a series of overnight operations carried out with the

bridge closed. As the contractors' method and risk assessments developed, this was accepted as a daytime operation with the bridge remaining open to traffic.

For each pier, 12 plinths were constructed in the bearing chamber below the pier and another 12 were constructed adjacent to the pier. Flat jacks contained within shear boxes with sliding plates on the top were then inflated to support the weight of the pier.

Prestressing cables had been passed under the pier and connected to steel beams at the far end. These cables were tensioned and at a load of around 2t the 900t pier began to slide. Once the pier had slid to a position where it was supported on 10 of the original plinths and was positioned over two of the adjacent plinths, the flat jacks on the new plinths were inflated to restore the number of support points to 12.

This process was repeated until the pier had moved out on to the plinths adjacent to the bridge. The piers were then secured and demolished using hydraulic breakers.

Installing the new bridge bearings

A requirement of the design was that no riverward load should be applied by the deck to the foundations. This was achieved by having a system of pot bearings at the South Pier react against a system of elastomeric bearings at the North Pier. After installation the north elastomeric bearings were pre-sheared such that, even at low temperatures, the horizontal bearing reaction is always landward. Extremely onerous differential displacement criteria had been set for the jacking period and to ensure that this was maintained



Fig 8. After installing the new bridge bearings

during the lowering of the bridge onto the new piers, the bearings were preloaded by a series of flat jacks that were inflated during a bridge closure using grout. The bridge remained closed until the grout had achieved its initial set and the deck was then jacked clear of the bearings and the bridge reopened. One week later, once the bearings had been fully grouted and the grout had achieved full strength, the bridge was finally lowered under a short term closure on to the pre-set bearings.

Control of the contract

Strathclyde Regional Council awarded the contract in March 1996 and in April 1996 the M8 through Glasgow was trunked and responsibility passed to the Scottish Office (now the Scottish Executive). As the Kingston Bridge project team had transferred to Glasgow City Council (GCC) to keep continuity of staff and protect the acquired knowledge of the problems with the bridge, the Scottish Office appointed GCC as its Agents for the works. At that time the designers were GCC assisted by Giffords & Partners with Scott Wilson as independent checker. Balfour Beatty was responsible for the design of the jacking control system and the bearings through its sub-contractor VSL with Halcrow

Crouch as its independent checker.

The collapse in autumn 1996 of a similar type of bridge in the Pacific Republic of Palau after similar strengthening operations prompted an in-depth review of the strategy to strengthen the bridge to ensure safety was not compromised.

The contractor, designer, engineer and client all had to agree that the jacking control system could meet the extremely onerous performance criteria necessary to keep the bridge within safe limits. No comparable operation of this type had ever been undertaken and the detailed design, checking and testing of the system was more involved than expected.

An external Project Manager was appointed by GCC and integrated site management and design teams were introduced to ensure agreement at all stages of the design and works. The contractual arrangements were also changed to Option E (Cost Reimbursable) to reflect the collaborative working that had been introduced.

Acknowledgement

Presented with the permission of Jim Barton, Director, Road Network Management & Maintenance Division, Development Department, Scottish Executive and Alastair Young, Director of Land Services Glasgow City Council.



Andrew Brodie graduated from Heriot-Watt University in 1971 and spent the next 15 years in Local Authorities with Bedfordshire CC, Grangemouth Burgh, Central Region, South Yorkshire CC, Dumfries & Galloway Region and Northumberland CC. 10 of these years were spent on the design, maintenance and assessment of bridges. Mr Brodie is the Scottish Executive's project manager for the strengthening works to the M8 Kingston Bridge Complex.



Ian Telford graduated from Heriot-Watt University in 1975 and joined Strathclyde Regional Council in 1979. In 1996 he moved to Glasgow City Council as part of the reorganisation of local government. Mr Telford is a Project Manager with GCC Land Services.

References

1. Fairhurst, W. A. *et al*, 'The design and construction of Kingston Bridge and elevated approach roads, Glasgow' *The Structural Engineer*, Vol. 49 No. 1, January 1971

REPORT

Subsidence of low-rise buildings (2nd edition)

Originally published in March 1994, the 1st edition of this guide has been the authoritative reference on the subject, and has led to many improvements in the way claims are handled, both procedurally and technically. The 2nd edition is being published to reflect current procedures and contains more comprehensive advice on tree management. While primarily aimed at Structural Engineers, the Guide is written for a wide readership including Mortgage Lenders, Consulting Engineers, Property Valuers, Insurers, Builders, Solicitors, Surveyors, Loss Adjusters, Local Authorities and property owners.

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