

# **A METHOD FOR INCREASING THE CAPACITY OF SHORT AND MEDIUM SPAN BRIDGES**

**Bridges / Strengthening / External post-tensioning**

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## **1 INTRODUCTION**

Over the last few decades, there has been a rapid increase in the volume and weight of heavy vehicles using national road networks. Consequently many road bridges which were built to previous design standards are not able to cope with the current traffic requirements and require either weight restriction, strengthening or even total replacement. This trend is very pronounced in developing countries where accelerated regional economic development has taken place. Many minor roads, which were originally built for light traffic, are being used by heavy vehicles that were not envisaged during the original design. In many cases, the road system provides the only means of transporting goods and people and its operation is vital for the survival and prosperity of large areas. There is a requirement, therefore, for methods of upgrading the carrying capacity of bridges cheaply and without causing too much disruption to traffic.

Various methods for strengthening bridges are available and are described in numerous textbooks and publications (eg, Xanthakos 1996). These include the replacement of damaged or under-strength members or components, addition of structural material using steel or reinforced concrete jackets, bonded steel plates, etc. Two methods that are currently proving to be very useful in increasing the capacity of short and medium span bridges are bonded fibre reinforced plastic (FRP) laminates and external post-tensioning. These methods can be applied to a wide range of structural types. The use of bonded fibre reinforced plastic laminates is dealt with in more detail in a companion paper (Daly 2000). This paper concentrates on the use of external post-tensioning, and presents criteria for its use and the advantages and disadvantages. Two examples of its application in Indonesia are presented to illustrate the use of this technique. Finally load tests carried out on a quarter scale model bridge at TRL are described and the conclusions in relation to bridge strengthening are presented.

## **2 NEED FOR STRENGTHENING**

The rapid growth in the volume and weight of heavy goods vehicles has resulted in a series of increases in the specified design loading for bridges since standardised loading was adopted near the turn of the century. Because of this, many in-service bridges do not conform to current design standards and, unless measurable reserves of strength exist, some form of strengthening or weight restriction is required. Other defects may also exist. Many bridges have suffered deterioration or damage, which has impaired their structural behaviour. This could be due to environmental conditions such as corrosion of steel members, corrosion of reinforcement in concrete, or due to wear and tear from normal or overloaded traffic. Damage could be due to vehicle impact on either sub-structures or super-structures.

Even if a bridge has been designed to current loading standards, there is always the possibility that it might be under-strength due to design or construction errors, sub-standard materials, etc. Detailed assessment is required to determine load carrying capacity and the necessity for structural repair or strengthening. Many countries have adopted formal bridge assessment programmes and some, such as the UK, have formulated codes of practice specifically for the assessment of existing bridges. These codes are based on the current design codes but are written from the point of view of assessment because of the different philosophical strategies required. This approach has been very successful in eliminating unnecessary strengthening projects.

Road network owners and managers throughout the world are facing increasing demands to ensure that the structures for which they are responsible are safe for the users and economic in terms of maintenance and repair requirements. There are competing demands for scarce resources (funds, manpower, etc), and the high costs of bridge rehabilitation projects demand that any planned activity

be fully justified in terms of benefits obtained. The main objective from the bridge management point of view is to keep bridges in service at minimum cost. Because of this, bridge engineers are naturally reluctant to commission bridge strengthening or replacement work. This has highlighted the need for quick and convenient bridge strengthening techniques.

### **3 SELECTION PARAMETERS**

A number of factors need to be considered when evaluating different methods for strengthening a particular bridge. These include the type of structure, the magnitude of the strength increase required and the associated costs. Many strengthening techniques are applicable to particular structural types and have limits on the extent to which strength can be increased. Strengthening costs would certainly be lower than bridge replacement, but the selection of a particular strategy must be justified on economic grounds. It is important to consider not only the initial capital costs of the strengthening project but also the maintenance costs associated with the future in-service behaviour. The condition of the existing bridge is an important consideration. If the bridge is in poor condition, then future maintenance and safety problems might override the benefits of the reduced initial costs of strengthening and provide justification for bridge replacement. The strength and condition of the sub-structure must not be ignored and strengthening should not proceed without considering the capacity of the bridge piers, abutments and foundations. The difficulties associated with traffic management and the costs arising from traffic delays should also be taken into account in the economic justification. In some cases, this may limit the use of certain methods of strengthening.

Depending on the bridge configuration and the expected service life of the bridge after strengthening, other factors might need to be considered before a particular scheme is adopted. The durability of the components of the rehabilitated bridge, and the ease with which they can be inspected and replaced, are very important aspects. For some strengthening systems, the ability to monitor the behaviour of the strengthened bridge might need to be considered, particularly where an innovative method is being used. The ability to adjust the level of strengthening in future to allow for further increases in traffic loads might provide a useful benefit.

An important consideration is the appearance of the bridge after strengthening and this should not be ignored. While bridge aesthetics have always played an important role in the design of major structures, public perception has often been ignored for short span bridges. This is now beginning to change and emphasis is being placed on how highway bridges look. The use of intermediate supports or props, or strengthening methods which appear unsightly, while tolerable as temporary measures, are becoming less acceptable as long term solutions.

Many strengthening techniques have general applicability, but some may be specific to particular bridge types and configurations. The decision to adopt a particular scheme is based on the consideration of a wide range of parameters. The remainder of this paper is concerned with external post-tensioning for bridge strengthening. The general principles, advantages and disadvantages are described in the following sections.

### **4 TECHNIQUE OF EXTERNAL POST-TENSIONING**

Strengthening by external post-tensioning is simply the application of an axial load combined with a hogging bending moment to improve the flexural and/or shear capacity of a structural beam or component. The method can also be used to improve serviceability. For example, the increased stiffness provided by external post-tensioning can reduce in-service deflections and vibrations. The stress range at a critical location can be also reduced thus improving fatigue performance, and the presence of a deformation or sag in a bridge can be reduced or removed. It is also possible to use post-

tensioning to change the structural behaviour in order to increase strength. For example, the strengthening objective might be to provide continuity across a support, ie, change a series of simply supported spans to a continuous one. It can also be used to provide continuity across an unsupported joint, for example, across the joint between two cantilever spans.

Post-tensioning for bridge strengthening has been in use since the 1950s and there are many examples throughout the world. In most situations, the load is applied through prestressing cables, either single or grouped strands. In some applications, the stress has been applied through high tensile bars, jacked either using hydraulic jacks or with fine screw threads. In a few cases, the stress is applied using more unconventional techniques. For example, stress in a tendon can be developed by anchoring a straight tendon in place and imposing a deflection at mid-span. The deflection is then retained by fixing the deflected point. Prestress can also be developed by applying a load to impose a deflection in the deck prior to anchoring the tendons or bars.

## **5 APPLICATIONS**

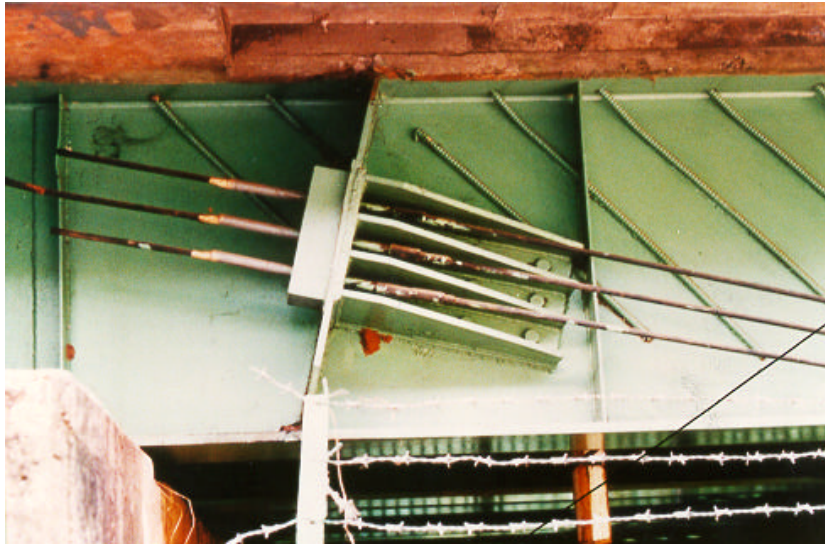
A number of bridges in Indonesia have been strengthened using external post-tensioning. These are described here to illustrate the technique.

### **5.1 Condet bridge, Indonesia**

Condet Bridge is a heavily trafficked steel beam and concrete slab composite bridge on the 4-lane highway between Jakarta and Citarum, which carries up to 30,000 vehicle per day with a large percentage of heavy trucks. It has three spans of 24m, 48m and 24m. It was built in 1989 and designed for full Indonesian Highway loading, but assessment after five years of service indicated that strengthening was required. External prestressing was applied in 1994 to rehabilitate the bridge to enable it to carry full design loading. As the bridge carried a high volume of traffic along a major route, immediate strengthening was required with minimal disruption to traffic. External post-tensioning was chosen as the preferred method of strengthening because of the minimal disruption to traffic, the low weight of the additional components, the speed and short duration of construction, and the low costs involved. In addition, future re-stressing operations could be carried out quickly and conveniently, if required.

All the beams were strengthened using two cables, each consisting of three 12.7mm high strength strands placed at an eccentricity of 2m over the middle third of the span. Each 7-wire strand was greased and individually sheathed in a polyethylene tube to provide protection against corrosion. The tendons were anchored near the support using specially fabricated anchor plates. The anchorage is shown in Figure 1. The strands were anchored using conventional barrels and wedges. The anchorage plates were initially installed using 16mm diameter bolts and then fixed permanently in place by welding. At the anchorages, the sheathing was removed from the strand for sufficient length to enable the wedges and stressing equipment to be installed. To reinstate the corrosion protection, a steel box was fabricated around the anchorage after stressing, fully enclosing the barrels and wedges. This was then filled with grease. Where the tendons protruded from the box, a steel pipe filled with grease was placed over the strands. All exposed parts of the strand and all joints in the sheathing were then covered with greased tape to seal the system completely.

Figure 2 shows the fully strengthened deck. Subsequent inspections of the bridge confirmed that it is functioning in a satisfactory manner and the strengthening system is in good condition. In 1995, exceptionally high floods occurred and all the tendons were submerged. This was unexpected and not considered during design, as the tendons are about 6m above normal water levels. To date, no formal inspection has been carried out to determine whether any corrosion damage problems might occur as a



**Figure 1 Anchorage used in Condet bridge.**

result of this or future re-occurrence. In spite of this, the tendons, anchorages and deviators appear to be in good condition based on close visual examination.

## **5.2 Kemplaka Gede Bridge, Indonesia**

Kemplaka Gede Bridge is on the main east-west link on the northern corridor of the island of Java. This road is heavily trafficked, carrying about 40,000 vehicles per day to and from the capital, Jakarta. The bridge has a single span of 17.7m and carries a 7.56m wide carriageway. The deck consists of five steel beams at 2m spacing with an in-site cast reinforced concrete composite slab. The purpose of the strengthening was to increase the capacity of the bridge to full highway loading so that no traffic restrictions were required.



**Figure 2 Condet Bridge after strengthening.**



**Figure 3 Kemlaka Gede bridge after strengthening.**

The strengthening details used for this bridge were generally similar to those of Condet bridge as described above. Each beam was strengthened using two cables, consisting of two 7-wire strands, 12.7mm in diameter. The deviators were fabricated from I-sections 300mm deep with 150mm flanges. The deviator tubes consist of two lengths of 50mm diameter pipe welded together. Figure 3 shows a general view of Kemlaka Gede Bridge after strengthening.

Load tests were carried out before and after strengthening. These indicated that the mid-span stresses in the steel beams were reduced by 30% to 50% showing that the strengthening was effective. After three years, the bridge was performing adequately but there are problems of corrosion in the strengthening system. The tendons are sheathed, but the sheath was removed at the anchorages. No supplementary corrosion protection was provided at these locations and surface corrosion is evident on all exposed tendons. It is not clear why the tendons were left unprotected in these critical locations. In addition, the end of the sheath, which is cut off before the anchorage, was not sealed and it is likely that it is not providing any protection. In fact, it may be serving as a water trap, allowing water to leak along the tendon to the deviator. It is likely that all tendons will require replacement in the near future.

## **6 TESTS ON A QUARTER SCALE MODEL BRIDGE**

This project was carried out as part of a research project commissioned by the UK Highways Agency to investigate the strength of externally post-tensioned concrete bridges. The project included a review of external post-tensioning as a means of strengthening bridges, as well as investigating design and construction guidelines for new construction. As part of the research, a quarter scale model bridge was constructed and load tested to failure.

### **6.1 Design and construction**

The model was designed as an externally post-tensioned structure and a suitable testing regime was devised to investigate its behaviour as it was loaded to collapse. However, many of the conclusions are equally applicable to the retrospective application of post-tensioning for strengthening existing

**Figure 4 Basic cross-section of model bridge.**

concrete bridges. Relevant topics include the calculation of flexural and shear capacity, the reduction of eccentricity, the increase in tendon force as the structure is loaded, prestress losses, corrosion protection, and the design of anchorages and deviators.

The bridge was designed to full scale by a UK consulting engineering firm using the current UK bridge design documents and BD 58 (Highways Agency, 1994) which specifically refers to external post-tensioning. Full details of the design are given by Daly and Jackson (1999). The bridge was a two-span continuous concrete box structure with spans of 32m and 48m, designed to carry normal HA loading and 45 units of HB loading, as defined in the UK bridge loading specification (Highways Agency, 1988). The bridge was then constructed to quarter scale at the TRL testing facility where two separate load tests to collapse were carried out. Details of the construction and load tests are presented by Woodward and Daly (1999). The cross section of the model bridge is shown in Figure 4. Figure 5 shows the model and loading system just prior to the first load test. The following sections contain a summary of the load tests and the conclusions in relation to strengthening applications.



**Figure 5 Model bridge ready for load test.**

## **Figure 6 Load deflection for load test 1.**

### **6.2 Testing**

The objectives of the tests were to monitor the behaviour of the model bridge as it was loaded to collapse and to compare the ultimate capacity with the analytical predictions based on various design codes. Of particular interest were the friction losses at the deflectors and supports, the increase in tendon force as the model was loaded, and the behaviour of the deflectors, support diaphragms and anchorages as the beam was loaded to failure. Two load tests were carried out as described in the following sections.

#### **6.2.1 Load test 1**

Test 1 was a flexural test in the main span with the load applied 5m from the end support. Load was applied using two stressing jacks placed on a cross-head positioned transversely across the model at the designated section. Strands passing through the cross-head and jack reacted against anchors installed in the base of the test bed. Load was applied using a single hydraulic pump that delivered equal pressure to the two jacks. The loading system can be seen in Figure 5. A full description of the load test is given by Woodward and Daly (1999).

The maximum load of 627kN was recorded at a deflection of 134mm. The load in the prestressing tendons had increased by 16% and the eccentricity in the cables was reduced by 38.7mm. As the beam was deflected further, the applied load reduced and the beam failed suddenly in flexure at a deflection of 201mm. Figure 6 shows the load deflection curve obtained during the load test to failure. The plot is annotated to indicate the sequence of damage occurring in the model. Figure 7 shows the damage in the model when the load test was completed. The ends of the beams, anchorages and deviator were carefully examined for cracks but none were observed.

#### **6.2.2 Load test 2**

Test 2 was a shear test with the load applied 1m from the end support in the shorter span. The loading methodology was similar to that used for the first test. The maximum load of 661kN was



recorded at a deflection of 19.8mm. At this stage, the total prestress in the section had increased by



**Figure 7 Failed model after load test 1.**

7% and the eccentricity was reduced by 11.7mm. The test was continued until the beam had deflected 100mm. The model was still carrying a load of 290kN when the test was finally halted. After removal of the load, the residual deflection was 5.4mm. Figure 8 shows the behaviour of the model bridge in graphical form and the damage occurring is shown in Figure 9. As for test 1, no damage was observed in the anchorages or deviators.

**Figure 8 Load deflection for load test 2.**



**Figure 9 Failed model after load test 2.**

### **6.3 Summary of conclusion from load tests**

A number of conclusions were drawn from the tests and these are listed here. More detailed discussion is given by Woodward and Daly (2000).

1. The model bridge behaved in a satisfactory manner as it was loaded to failure in two separate load tests. No cracking was observed at the anchorages and deviators.
2. The external post-tensioning system was easily installed, operated and monitored. The method provides a useful technique for strengthening existing bridges which can be applied easily and economically to a range of different structure types.
3. The effect of loss of effective prestress due to reduced eccentricity can be mitigated by careful positioning of deviators.
4. Flexural capacity: conservative estimates were obtained from all codes used. Increase in tendon force can be taken into account if the tendon profile is designed to minimise reduction of eccentricity.
5. Shear capacity: conservative estimates were obtained from all codes. BD 58 in particular produced a very conservative result for this test configuration.
6. There was little capacity for load re-distribution at the central support when the model bridge was loaded at the centre of the longer span. This is a consequence of the mode of failure and the disruption to the concrete section at the load point. This, along with the limited overall ductility of the model, has implications for the use of re-distribution of moments for bridges of this type. It is important that designers ensure that sufficient ductility exists before re-distribution of moments is utilised.
7. Care needs to be taken when additional stresses are imposed on an existing structure and a careful condition survey is required.

8. The long-term durability of the external post-tensioning system and the corrosion protection requirements are still largely undefined. New materials, such as fibre reinforced plastic tendons, may provide attractive alternatives due to their resistance to corrosion.

## 7 CONCLUSIONS

The technique of external post-tensioning has been shown to provide a useful method for strengthening short and medium span bridges. The practical applications described demonstrate the flexibility of the system and the ease with which it can be installed with minimal disruption to traffic. The load tests on a quarter scale model at TRL have shown that the method can provide a safe and stable method of strengthening, although care needs to be taken to provide protection against corrosion.

## 8 ACKNOWLEDGEMENT

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## 9 REFERENCES

Daly, A F (2000). *Use of fibre reinforced plastics for the strengthening of concrete bridges*. Paper submitted to 10th REAAA Conference, Tokyo, Japan.

Daly, A F and P Jackson (1999). *Design of bridge with external prestressing: Design example*. TRL Report 392, Transport Research Laboratory, Crowthorne, Berks, UK.

Highways Agency (1988). BD 37/88, Loads for highway bridges. *Design manual for roads and bridges*, Volume 1, Section 3, Highways Agency, London.

Highways Agency (1994). BD 58/94: The design of concrete highway bridges and structures with external and unbonded prestressing. *Design Manual for Roads and Bridges*, Volume 3, Section 3, Part 9, Highways Agency, London, UK.

Woodward, R J and A F Daly (1999). *Design of bridges with external prestressing: Construction and load testing of a model bridge*. TRL Report 391, Transport Research Laboratory, Crowthorne, Berks, UK.

Woodward, R J and A F Daly (2000). *Strengthening of bridges using external prestressing*. TRL Annual Review 2000, Transport Research Laboratory, Crowthorne, Berks, UK.

Wawan, W, and A F Daly (1997). *Strengthening of bridges using external unbonded tendons*. Paper presented at EASTS 97 conference, Seoul, 29-31 Oct, 1997.

Xanthakos, P P (1996). *Bridge strengthening and rehabilitation*. Prentice Hall, New Jersey.