DEPARTMENT OF TRANSPORT   **BA 30/94**

THE SCOTTISH OFFICE INDUSTRY DEPARTMENT

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THE DEPARTMENT OF THE ENVIRONMENT
FOR NORTHERN IRELAND

Strengthening of Concrete Highway Structures Using Externally Bonded Plates

Summary: This Advice Note refers to the technique of strengthening concrete highway
structures by external plate bonding

REGISTRATION OF AMENDMENTS

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VOLUME 3	HIGHWAY STRUCTURES: INSPECTION AND MAINTENANCE
SECTION 3	REPAIR AND STRENGTHENING

PART 1

BA 30/94

STRENGTHENING OF CONCRETE HIGHWAY STRUCTURES USING EXTERNALLY BONDED PLATES

Contents

Chapter

1. INTRODUCTION

General

1.1   This Advice Note deals with the strengthening of concrete structures by bonded steel plates and is based on current experience and practice.

1.2   The technique of bonding steel plates to concrete bridges using epoxy adhesives has been used on a number of trunk road structures to enhance their load carrying capacity. The technique has proved successful over a period exceeding fifteen years. The viability of this technique for a particular structure should be considered carefully due to its sensitivity to standards of workmanship and need for regular in-service inspection. Economical evaluation should be carried out in order to compare this technique with other methods of strengthening.

1.3   The effect of bonding a plate to the tension face of a reinforced concrete section is to increase the depth from the compression face to the neutral axis and the area of effective reinforcement, thus, increasing the moment of resistance of the section. The operation is undertaken without additional support to the member. Generally the bridges remain open to traffic during the bonding operation.

Mutual Recognition

1.4   The strengthening of highway structures will normally be carried out under contracts incorporating the Overseeing Department's Specification for Highway Works (Manual of Contract Documents for Highway Works Volume 1). In such cases products conforming to equivalent standards and specifications of other member states of the European Economic Area and tests undertaken in other member states will be acceptable in accordance with the terms of the 104 and 105 Series of Clauses of that Specification. Any contract not containing these Clauses must contain suitable clauses of mutual recognition having the same effect regarding which advice should be sought.

Scope

1.5   Recommendations are given on the provision of flexural strengthening by bonded steel plates to reinforced and prestressed concrete members in locations amenable to inspection. In prestressed concrete ensure that stress transfer due to creep in the concrete will not result in excessive compressive forces being induced into the plates.

Durability

1.6   At present there are no standard accelerated laboratory testing methods to predict the long term performance and durability of the system, particularly in the application to bridges.

Implementation

1.7   This Advice Note should be used forthwith on all schemes involving the strengthening of concrete highway structures on trunk roads, including motorways. The case for using the technique must be submitted to the Technical Approval Authority as defined in BD2 (DMRB 1.1) for acceptance in principle before detailed design proceeds.

2. APPLICATION OF THE TECHNIQUE

General

2.1 The technique of bonding steel plates to soffits can be applied to all bridge decks, except those over carriageways where headroom is critical or where there is evidence of frequent damage to the soffit from vehicles. A bridge deck will only be considered suitable for strengthening by plate bonding if it can be shown to be at least capable of supporting nominal dead load, superimposed dead load factored by $\gamma_{fL} = 1.2$, and nominal HA live load (i.e. unfactored) when checked at ULS.

Case Studies

2.2 Five case studies of plate bonding on bridge decks, in this country, are included in **APPENDIX B.** In Japan over 2500 reinforced and prestressed concrete highway structures have been strengthened by this method. It has also been applied to 64 non-highway structures. There are reported cases of successful application of plate bonding in South Africa, America and Europe.

Investigations and Tests

2.3 Before plate bonding is considered for a structure, investigations should be carried out to ensure that the risk of corrosion in the existing member is low and that the structure is sound enough (including any repaired areas) for strengthening by plating. BA 35 (DMRB 3.3) The Inspection and Repair of Concrete Highway Structures gives advice on special inspections and guidance on suitable tests. In Scotland, this advice is given in SB 1/78.

2.4 Plate bonding, as with other rehabilitation methods, has limitations. Surfaces that are damp or subject to leakage, particularly if contaminated with chlorides should only be plated after satisfactory remedial measures have been taken. If the reinforcement is corroding the expansive rust products may disrupt the concrete and eventually cause debonding of the plate. Therefore unless repairs have been carried out plate bonding should only be considered for members where chloride values are generally less than 0.3% by weight of cement and half-cell potential measurements are numerically generally less than - 350mv
(eg - 200mv) with respect to a copper/copper sulphate electrode.

Headroom

2.5 Where plating to soffits above carriageways is being considered the available headroom should be checked. Due allowance should be made for the location of bolts required at the ends of the plate to resist peeling stresses and those bolts along the length of the plate which would provide temporary support should debonding occur.

Methods

2.6 The bonding of steel plates to concrete members has been undertaken by several methods, the choice of method being dependent upon the particular circumstances. Three methods are given below:

i. Single plates of the required thickness. A paste consistency resin is applied to the plate which is pressed into position against the soffit by wedging off a temporary stiff girder. The stiffness of these plates will not allow them to follow the concrete profile closely and variations in adhesive thickness will be apparent. A minimum adhesive thickness is maintained by the use of plastic spacers. Bonding can proceed quickly, although the quantity of adhesive used is increased.

ii. Multiple plates bonded in layers to give the required total thickness. Adhesive is applied to the plates and is offered to the soffit as described above. The advantages are that thinner, more flexible plates can be used which follow the profile of the existing concrete surfaces and a thin, constant thickness glue line is maintained. The disadvantage is a longer construction period.

iii. Single plates of the required thickness and the gaps sealed at the edges between the steel and the concrete. Resin is then pumped ensuring that no voids occur between the plate and the concrete. This method is economical of resin and quick but difficulties may arise over maintaining the standard of surface preparation of the steel due to greater time lapse between steel preparation and final resin injection.

Moisture Protection

2.7   To protect the adhesive against moisture ingress the edges of the plate should be sealed with a resin putty or mortar after the adhesive has cured. A suitable chamfer/fillet could also be formed in the adhesive around the edge of the plates and the concrete surfaces.

Corrosion Protection

2.8   It is fundamental to the long term durability of the plate bonding technique that the plates and all associated components be adequately prepared and protected. Appropriate protection system should be selected, having considered relevant environmental aspects (ie type of exposure, inland or marine).

3. DESIGN

Limit States

3.1   The design of strengthened structures should be considered for the serviceability and ultimate limit states in accordance with the relevant clauses of BS 5400: Part 4: 1990 as implemented by BD 24 (DMRB 1.3), except where amended by other clauses in this Advice Note. The appropriate loads and load factors should be taken from BS 5400: Part 2 as implemented by BD 37 (DMRB 1.3). A sample calculation is included at **APPENDIX D.**

Partial Safety Factors

3.2   Partial safety factors for structural steel plates of $\gamma_m = 1.05$ for ULS and $\gamma_m = 1.00$ for SLS should be used. Where the characteristic strengths of the existing concrete and reinforcement are not known characteristic strengths may be derived from test evidence. Guidance on the assessment of material strengths is given in BD 21 (DMRB 3.4).

Brittle Failure

3.3   The over reinforcement of a concrete section can result in a brittle failure. Sections to be strengthened should therefore be checked to ensure that this does not occur, in particular by using the requirements of Clause 5.3.2 of BS 5400: Part 4: 1990.

Plate Dimensions and Spacing

3.4   When determining the size and thickness of single plates for use in strengthening the following requirements should be applied:

i.   The width to thickness ratio, b/t, should not be less than 50.

ii.   Minimum plate thickness should not be less than 4mm in order to avoid distortions during grit blasting and handling on site. The loss of section which may occur during grit blasting should be taken into account in the calculations.

iii   The transverse clear distance between the plates should not be greater than twice the overall depth of the member less 100mm.

Fatigue

3.5   The stress range in the plate under load combinations 1 to 5 should not exceed 150 N/mm² at SLS.

Anchorage Length

3.6   The effective anchorage length, l_a, at the end of the plate should not be less than 1.5b for b/t of 50 and for b/t equal to or greater than 60, the anchorage length should not be less than 1.2b. For curtailment purposes a nominal length of 100mm should be added to the above anchorage length.

Bolts

3.7   Bolts should be provided in the anchorage length to resist 3 times the ultimate limit state longitudinal shear stress (ref 6), and to be adequately anchored into the concrete substrate.

3.8   Bolts required to temporarily support plates in the event of debonding should be designed to the serviceability limit state. In many cases it will be appropriate to consider construction loads and state a maximum allowable load on the drawings. The bolt spacing should be sufficient to prevent deflection of the debonded plate within the defined headroom. Precise plotting of the existing reinforcement with an accurate covermeter is essential. Plates can then be fabricated with holes positioned to allow the fixing bolts to avoid the reinforcement.

3.9   Concrete structures to which plates are to be bonded will invariably have imperfections of surface profile. If the steel plates are made to follow these imperfections, additional stresses will be induced in the steel plate, the adhesive and the concrete. Additional secondary stresses may also be induced under subsequent loading, eg tensile stress on the plate will tend to straighten the plate out causing stresses normal to the plate in the adhesive. Plates should not extend into areas of compression as plate buckling may occur causing tensile/peel stresses in the adhesive. Where this cannot be avoided, bolts should be provided at a spacing not exceeding 32t, where t is the thickness of the plate, or 300mm whichever is the lesser. [BS 5400: Part 3, C1 14.5.1.2]. Alternatively, where the compressive stress in the plate is low, the spacing of the

bolts may be determined by elastic critical buckling
analysis assuming the plate to be a two-pinned strut
with allowances for imperfections and ignoring lateral
restraint from the adhesive. In this case maximum bolt
spacing is restricted to 300mm.

4. MATERIALS

Steel Plates

4.1   Plates to comply with BS EN 10 025 Fe 430 (ref 18). The use of high yield steel does not generally provide benefits as the modulus of elasticity is the same as mild steel. Stainless steels should not be used as there is little published information on the effect of its composition on the adhesive bond strength.

Concrete Suitability

4.2   A range of tests are available for determining the suitability of the concrete surface for bonding plates. The most suitable test method involves bonding a metal dolly to the concrete and subsequently pulling it off. Examination of the failure mechanism and failure load gives useful guidance. An instrument for carrying out such a test is mentioned in reference [7].

Adhesive

4.3   On the basis of the Department of Transport's long term experience epoxy resin adhesives have been found to be suitable for steel plate bonding. Their durability has been established by use over a period of fifteen years. Epoxy resin adhesives are therefore acceptable for strengthening proposals provided that they comply with the specification given in **APPENDIX A**. This specification contains provisions for the acceptance of alternative equivalent adhesives.

4.4   Epoxy resin adhesives require care in use. Manufacturers or formulators commonly supply two-part resins in containers suitably proportioned for mixing. It is important that all the hardener is added to the resin in its container and mixed with a slow speed mechanical mixer. High speed mixing entrains air and is less efficient. The resin and hardener should be of different colours and a uniform colour indicates adequate mixing. The speed of the chemical reaction increases with the temperature generated.

Application of Adhesive

4.5   It is important to spread the adhesive immediately after mixing to dissipate the heat generated and extend its workability time. Common practice is to spread the adhesive slightly more thickly along the centre line of the plate than at the sides of the plate. This reduces the risk of forming voids when pressing the plate loaded with adhesive against the concrete surface. Excess adhesive can then be scraped away. The use of plastic spacers maintains the minimum adhesive thickness of 1-2mm. Procedure trials should always be carried out to prove the method of application and acquaint the operatives with the material. When temperature is less than 10ºC, artificial heating may be required to assist curing and maintain the ambient temperature and humidity at acceptable levels. Where resin is to be injected mixing takes place during injection. The procedure to fill the gap between the plate and the concrete is to inject the resin through a pipe which is gradually withdrawn as filling takes place. Procedure trials should be carried out to prove the method. The manufacturer's instructions on safe use of resins should be followed.

5. SURFACE PREPARATION AND TRIAL PANEL

Concrete Surfaces

5.1 The concrete surface of an existing member will usually be contaminated and have out-of-plane imperfections and will therefore require preparation before plates are bonded to it. Grit blasting is a preferred method of removing weak material, laitence and surface contamination. Scabbling and grinding could damage the concrete and should only be used to remove minor protuberances. Cracks wider than 0.2mm which could allow loss of adhesive and areas of concrete that appear porous should be sealed with a compatible resin. The prepared surface should be dust free and surface dry. If moisture is picked up by absorbent paper pressed onto the concrete it is likely to be too damp for bonding. A heated enclosure may then be necessary.

Steel Surfaces

5.2 The surface of the steel to be bonded must be completely free of any mill-scale, rust, grease or other contaminants. For successful adhesion of the resin the contact surfaces of the steel plates should be degreased and blast cleaned at the fabricators premises to grade Sa 2½ of ISO 8501-1 (International Organisation for Standards) as implemented by BS 7079: Part 1 using clean hard angular metal grit, free of contamination to give a blasted surface (peak to trough) amplitude between 50 and 100 microns. All surface dust on the plates should be removed by vacuuming immediately before application of the primer. The primer, for the epoxy resin adhesive (paragraph 4.3), should be an epoxy based system which is compatible with the adhesive. It should be applied to the surfaces to be bonded at a dry film thickness not exceeding 50 microns within 4 hours of grit blasting and allowed to cure for the time specified by the manufacturer at the appropriate temperature. The primer for the alternative adhesive should be compatible with the adhesive and should be applied in accordance with the manufacturer's instruction. Subsequent handling should be undertaken by operatives wearing clean gloves. The plates should be wrapped in clean protection material in the presence of a desiccant and stored in clean dry conditions. Before the application of the adhesive, the surface of the plate to be bonded should be degreased with material approved by the Engineer and then completely dried.

Care is needed to prevent warping of plates during grit blasting and tolerances should therefore be specified for straightness. Where the adhesive is applied by injection, the interval between grit blasting on site and injection of the material should not exceed four hours to reduce the degree of deterioration of the steel surface. Alternatively, the plate surfaces could be prepared as described above.

Trial Panel

5.3 A trial panel strengthened with steel plate should be constructed in order to demonstrate to the Engineer the suitability of preparation of concrete surfaces, fixing of spacers, application of resin, installation of the plate, method of adoption for application of pressure to the plate during gelling and curing of the adhesive.

6. QUALITY CONTROL

Testing Authority

6.1   An independent testing authority should be appointed to carry out an examination of the workmanship and the testing of the materials to the approval of the Engineer. The tests stated in 6.2 and 6.3 should be undertaken.

Flexural Modulus of Elasticity

6.2   Adhesive - For each batch of adhesive mixed the contractor should manufacture one prism of adhesive for the subsequent determination of the flexural modulus of elasticity. The specimens should be of the dimensions given in **APPENDIX A,** clause 13, manufactured in steel moulds and allowed to cure in the same ambient conditions and for the same period of time as that used in the bonding operation. The samples should be load tested as stated in **APPENDIX A**, clause 13. The test should be deemed acceptable if the secant modulus value is $\pm$ 2KN/mm^2 of the average of the five tests results as stipulated in **APPENDIX A**, clauses 10 and 13.

Shear Tests

6.3   Bond to Steel - double overlap shear tests (**APPENDIX A**, clause 15). Three number double lap shear tests should be performed for each batch delivered to the site. The mild steel adherents should be prepared in the same manner as the plates to be bonded. The load at failure to be recorded and reported, and the test should be deemed acceptable if the bond strength of the adhesive to the steel is greater than 8 N/mm^2.

7. IN-SERVICE INSPECTION AND MAINTENANCE

Manual of Procedures

7.1   The Engineer should prepare a manual of procedures for inspection and maintenance for the strengthened structure for the Maintaining Agent. A typical summary of inspection procedures is included at **APPENDIX C** but this should not be regarded as exhaustive. A draft list prepared during design can be extended during construction should it become necessary.

7.2   Inspections should take place every six months for at least two years after completion of the works. The frequency of further inspection should be agreed with the Overseeing Department after a review of the inspection reports (ref 8 and 9).

7.3   The inspection procedure manual should include all relevant technical literature relating to products used in the works. Photographs of critical details and maps of cracking are also useful. Procedures to be adopted should deficiencies occur should also be clearly defined.

7.4   In the absence of a manual in the case of existing strengthened structures, the manual should be prepared by the Maintaining Agent.

Abnormal Loads

7.5   If an abnormal load is routed over a bridge which has been plated, an inspection should be carried out before and after its passage. The Maintaining Agent should have regard to the effect on the plates when deciding the extent of any monitoring required and whether inspections for future abnormal loads will be necessary.

8. REFERENCES

Publications referred to in the text and calculations

1.   BD2 (DMRB 1.1) Technical Approval of Highway Structures on Motorways and Other Trunk Roads.

2.   BA 35 (DMRB 3.3) The Inspection and Repair of Concrete Highway Structures.

3.   SB 1 (DMRB 3.1) (Scotland). The Inspection of Highway Structures.

4.   BD 24 (DMRB 1.3) Design of Concrete Highway Bridges and Structures, Use of BS 5400: Part 4: 1990.

5.   BD 37 (DMRB 1.3) Loads for Highway Bridges.

6.   BD 21 (DMRB 3.4) The Assessment of Highway Bridges and Structures.

7.   Bresson, J. Nouvelle recherches et applications concernant l'utilisation des collages dans les structures. Béton plaqué. Annales de l'Institut Technique du Batiment et des Travaux Publics, Suppl. No. 278, Paris 1971.

8.   BS 1881: Part 207 - Recommendations for the assessment of concrete strength by near-to-surface tests.

9.   Bridge Inspection Guide. HMSO 1983.

10.   TRMM 2/88 Trunk Road and Motorway Structures - Records and Inspection.

11.   Macdonald, M D. The flexural performance of 3.5m concrete beams with various bonded external reinforcements. TRRL Report SR 728: Transport and Road Research Laboratory, Crowthorne 1982.

12.   Ladner, M and Weder, C. Concrete structures with bonded external reinforcement. EMPA Report 206, Dubendorf 1981.

13.   BS 5350: Part B4 - Determination of pot life

14.   BS 5350: Part C5. Determination of bond strength in longitudinal shear.

15.   ISO 75: 1987 - plastic and ebonite - Determination of temperature of deflection under load.

16.   BS 2782 Part 3. Method 320 B/C.

17.   BS 2782 Part 8. Method 835C.

18.   BS 6319 Part 8. Method for the assessment of resistance to liquids.

19.   BS EN 10 025 - Hot rolled products of non-alloy structural steels and their technical delivery conditions.

20.   ISO 8501-1 Preparation of steel substrates before application of paints and related products.

Other useful references on plate bonding

20.   Calder, A J J. Exposure tests on externally reinforced concrete beams - first two years. TRRL Report SR 529: Transport and Road Research Laboratory, Crowthorne 1979.

21.   Calder A J J. Exposure tests on externally reinforced concrete beams - performance after 10 years. Department of Transport, TRRL Report RR 129, Transport and Road Research Laboratory, Crowthorne 1988.

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23.   Irwin, C A K. The strengthening of concrete beams by bonded steel plates. TRRL Report SR 160: Transport and Road Research Laboratory, Crowthorne 1975.

24.   Lloyd, G O and Calder, A J J. The microstructure of epoxy bonded steel-to-concrete joints. TRRL Report SR 705: Transport and Road Research Laboratory, Crowthorne 1982.

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26.   Mays GC and Hutchinson AR - Engineering
Property requirements for structural adhesives.
Proceedings of the Institution of Civil Engineers.
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27.   Mays GC and Hutchinson AR - Adhesives in
Civil Engineering. Cambridge University Press 1992.

28.   Raithby, K D. External strengthening of
concrete bridges with bonded steel plates. TRRL
Report SR 612: Transport and Road Research
Laboratory, Crowthorne 1980.

29.   Swamy R N et al. Structural behaviour of
reinforced concrete beams strengthened by epoxy-
bonded steel plates. The Structural Engineer, February
1987.

30.   Swamy R N et al. The effect of external plate
reinforcement on the strengthening of structurally
damaged RC beams. The Structural Engineer.
February 1989.

31.   Swamy R N et al. Plate separation and
anchorage of reinforced concrete beams strengthened
by epoxy-bonded steel plates. The Structural Engineer.
March 1988.

9. ENQUIRIES

All technical enquiries or comments on this Advice Note should be sent in writing as appropriate to:-

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SPECIFICATION FOR EPOXY RESIN ADHESIVES FOR STEEL PLATE BONDING

Materials

1. Two-part cold cured, epoxy based adhesives comprising resin and hardner. The resin shall be based on the diglycidyl ether of `bisphenol A' or `bisphenol F' or a blend of the two. The hardener, or curing agent shall be from the polyamine group in order to achieve a better resistance to moisture penetration through the adhesive layer. Inert fillers may also be incorporated with the resin component to improve the application or performance characteristics of the adhesive. The filler shall be an electrically non-conductive material, be highly moisture resistant, be able to withstand temperatures up to 120ºC without degradation and have a maximum particle size of 0.1 mm.

2. The materials shall be supplied in two packs, in correct weights for site mixing. The two components shall have different colours in order to aid thorough mixing.

3. Other adhesives offering performance equivalent to that provided by this specification and long term durability will be acceptable. In the absence of satisfactory laboratory accelerated durability tests, however, the assessment of the durability of an alternative adhesive will be based on the provision of evidence that it has, in practice, performed satisfactorily in conditions similar to the use proposed for a period of not less than 15 years after installation.

Mixing

4. Mixing to accord with manufacturer's instructions.

Placing

5. The adhesive shall be capable of being applied readily to both concrete and steel surfaces in layers from 2-10mm thick, or being pumped as described in clause 2.6 (iii) of Chapter 2.

Cure Time and Temperature

6. The adhesive shall be capable of curing to the required strength between $10°C$ and $30°C$ in relative humidities of up to 95%. For repairs and strengthening works the adhesive shall cure sufficiently to give the specified mechanical properties at $20°C$ in not more than three days. On curing the adhesive shall undergo negligible shrinkage.

Useable Life

7. Mixed adhesive, before application to the prepared surfaces shall have a useable life in excess of 40 minutes at 20ºC. Test method as in BS: 5350 Part B4 (ref 12).

Open Time

8. The time limit in which the joint shall be made and closed shall exceed 20 minutes at a temperature up to 20ºC. Test method as in BS 2782: Part 8 Method 835 (ref 14).

Storage Life

9. Shelf life of both the resin and the hardener shall be not less than 6 months in original containers at $5°$ - $25°C$.

Mechanical properties of hardened adhesive

General

10. Cure and storage temperature, as stated in the appropriate standards shall be used for all tests and a minimum of five tests undertaken for each test requirement and the average of the results taken.

Moisture Resistance

11. Minimum moisture transport through the adhesive shall be achieved, with water content not exceeding 3% by weight after 28 days immersion in distilled water at $20°C$. Specimens shall be 40 x 40 mm and between 1-2mm thick. Use the procedure and calculations in accordance with BS 6319: Part 8, Clause 6.2.7 (ref 17) to determine water content.

Heat Distortion Temperature

12. Temperature resistance. The adhesive shall have a heat distortion temperature (HDT) of at least 40°C. The sample under test shall be placed in a temperature controlled cabinet at 20°C and loaded in order to achieve a maximum fibre stress of 1.81 MNm^{-2} in accordance with ISO 75: 1987 (ref 14). The HDT shall be taken as the temperature attained, measured by a thermocouple attached to the specimen, after undergoing a further 0.25mm deflection while subject to a surface heating rate of 0.5°C per minute.

Flexural Modulus

13. Flexural modulus, without creep effects, at 20°C shall be in the range of 4-10KN/mm². A specimen 200 x 25 x 12 mm deep tested in four point bending shall be used. The sample shall be loaded at the third points to achieve a deflection at a rate of 1 mm/min and the central deflection recorded. From the resultant load-deflection curve the secant modulus at 0.2% strain is calculated.

Tensile Strength

14. A minimum value of 12 N/mm² at 20°C shall be achieved. A dumb-bell specimen in accordance with BS 2782 : Part 3 (methods 320 B/C) (ref 15) and having a cross-section of 10 x 3 mm. The specimens shall be cast in polytetrafluoroethylene-lined moulds. Adhesive ductility may be measured with appropriate strain monitoring equipment.

Lap Shear Strength

15. Tests shall be carried out over a range of temperatures specifically including - 25°C, + 20°C and + 45°C using bright mild steel adherents. The temperatures shall be measured by means of thermocouples attached to the steel surface of the joint using a double overlap joint as shown below. The minimum average lap shear stress shall be 8 N/mm² at 20°C. The ends of the main test pieces shall be debonded to avoid load being transferred in tension, and any adhesive spew at the ends of the side laps shall be carefully removed. Testing procedure as given in BS 5350 Part C5 (ref 13) shall be used.
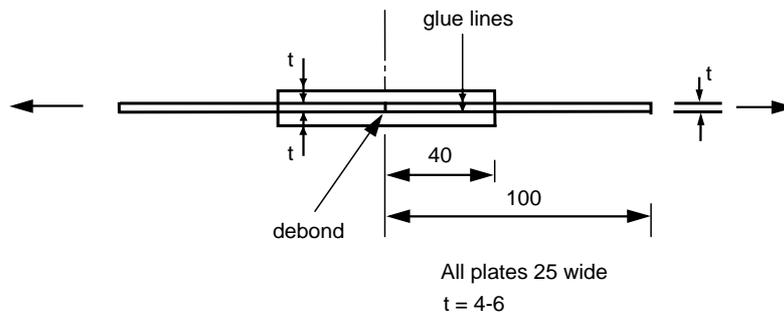
DOUBLE OVERLAP JOINT
(All dimensions in millimetres)

CASE STUDIES

1. Quinton Bridges (M5) 1975

The first major application in this country of bonded external reinforcement to a highway structure was carried out on four bridges forming part of the Quinton Interchange on the M5 near Birmingham. During assembly plates were suspended on bolts anchored in the deck soffit. After application of the adhesive the plates were pressed into position by wedges acting against a waling supported by the bolts. This type of arrangement ensures a uniform pressure on the plate over irregularities in the concrete surface. In some locations 4 layers of plates were used. After curing of the adhesive and removal of the waling the bolts were tightened and cut to length. The bridges remained open during the bonding operation as traffic vibrations were not considered to have any significant effect on the strength of the adhesive joint. The epoxy resin adhesive used is no longer formulated.

Full scale loading tests were carried out on one of the four bridges before and after strengthening. Strains and deflections due to a 400 kN single axle load were measured at various locations on the concrete deck and on the external steel reinforcement. Comparison with a grillage analysis confirmed the effectiveness of the method.

Following a recent inspection a limited amount of debonding has been observed on one of the 192 plates where it was exposed to chloride contaminated water from leaking joints. Corrosion was found progressing from the edge of the plate at the interface between the steel and the resin. There was also some evidence to suggest that corrosion had also been initiated by leakage through deficiencies in the concrete deck.

2. Swanley Interchange (M25) 1977

Bonded steel plates were used to longitudinally strengthen two, 3-span reinforced concrete bridges on Swanley Interchange following observation of cracks in their soffits after construction. The method was chosen as being quick, economical and causing the least disruption to traffic. Plates were bonded to the soffit of the longer side span to each bridge, the shorter side span of one bridge and on the top surface of the deck over each pier. 250mm x 6mm plates up to 6m in length were chosen for ease of handling and flexibility to conform to the concrete surface profile. Up to 3 layers of plates were bonded together to form continuous 12m strips with the required cross sectional area.

Plates were secured at the ends by bolts or clamps with no intermediate fixings. Sandbags were used to hold down plates on the top surface of the deck during curing while the soffit plates were wedged off beams supported on scaffolding. Traffic was diverted from one bridge and restricted to single lane working on the other during the works. Double lap shear tests, used as a quality control of the adhesive, were also used to ensure that no adverse effects would ensue from the hot rolled asphalt surfacing applied over the plates.

Loading tests were carried out before reopening the bridge to traffic. Various permutations and combinations of 22, 24 and 30 T lorries were used to generate the maximum moments at plated sections. Measured deflections were less than those predicted. A manual of recommendations for the inspection and maintenance of the bridges was drawn up by Kent County Council which includes contingency plans in the event of deficiencies occurring.

3. Brinsworth Road Bridge (M1) 1982

Brinsworth Road Bridge is a single span, 45° skew, simply supported deck consisting of pre-stressed concrete box beams; The beams were transversely post-tensioned parallel to the abutments and additional transverse reinforcement was required to enable the deck to carry heavy abnormal loads. A particular feature of this application was the 25mm step between beams due to the crossfall of the deck which meant a varying thickness glue line.

Tests confirmed that at design stresses this varying thickness of adhesive performed satisfactorily and also that there were no adverse effects due to strain from traffic loading during curing.

Adhesive was spread onto plates suspended from bolts located between the beams. The bolts also provided support for walings to wedge the plates during cure and remained in place to prevent dropping of plates in the event of debonding.

4. Stainsby-Teversal Road Bridge (M1) 1986

This single span simply supported reinforced concrete underbridge was strengthened longitudinally with steel plates. The 10mm thick steel plates used were too stiff to follow the profile of the deck soffit and it was necessary

to inject the resin after placing the plates in position. Experience gained from this approach suggested that the plate and its support system should be designed to allow a maximum plate deflection of 1mm at a resin injection pressure of 0.2 N/mm² with a maximum allowable pressure of 0.5 N/mm². A trial was carried out to ensure that on completion the resin completely filled the void. A maximum time between steel surface preparation and resin injection was specified to prevent corrosion affecting the adhesive bond.

5. Brandon Creek Bridge (A10) 1985

Strengthening of the deck cantilever was required on this bridge to support a new higher containment parapet. Plates were bonded to the top of the deck, pressure being maintained by sandbags. Traffic flow was maintained throughout the operation. After bonding the plates were painted to prevent corrosion and covered by the footway surfacing.

SUMMARY OF INSPECTION PROCEDURES

Deck Soffit Checks to Ensure

1.   There is no visible evidence of the sealed cracks
        in the concrete opening.

2.   There is no visible evidence of the plates
        debonding.

3.   By tapping the plates with a suitable light
        hammer there is no audible evidence of the plates
        debonding.

4.   The plate fixing bolts are not loose.

5.   The paint system is satisfactory as regards
        general film thickness and local breakdown of
        system.

Top-of-Deck Checks to Ensure

1.   There is no visible evidence of the road surfacing
        cracking or deforming.

2.   There is no visible evidence of any cracks in the
        coping increasing in width or new cracks
        forming.

3.   There is no rust staining from cracks in the
        coping.

WARNING

Do not damage protective paint system by hammer
tapping or slacken nuts on bolting system.

EXAMPLE OF DESIGN CALCULATIONS FOR STRENGTHENED DECK SLAB

General

1. This example is presented as an illustration of the design method for strengthening a slab with bonded steel plates. The details of the example have been simplified by considering only load combination 1 with HA loading and by including only those calculations directly concerned with the sizing, width and positioning of the bonded plates.

2. The structure is a solid reinforced concrete bridge deck slab simply supported over an effective span of 16.5m. The bridge supports a 7.3m wide carriageway with 1.5m wide verges, giving an overall width of 10.3m. The 850mm thick concrete deck has a depth of surfacing of 120mm, including waterproofing. Longitudinal reinforcement in the deck consists of 25mm diameter bars arranged in pairs at 150mm centres.

3. The bridge had been designed to support HA loading and has subsequently suffered cracking in the soffit of the slab. Inspection of the slab has revealed sound uncontaminated concrete with crack widths in the soffit, under dead load, not exceeding 0.2mm. To improve crack control under live loading the section must be stiffened so as to increase its effective second moment of area by at least 12% when resisting live loads. To achieve this externally bonded plate reinforcement is to be attached to the bridge soffit.

4. **Material properties:**

Concrete:	f_{cu}	=	40 N/mm²
	E_c	=	31 kN/mm²*
Reinforcement bars:	f_{yl}	=	460 N/mm²
	E_{sl}	=	200 kN/mm²
Additional steel plate:	f_{y2}	=	265 N/mm²
	E_{s2}	=	200 kN/mm²

* short term value from Table 3 BS 5400: Part 4

5. **Loading**

Using the loads and load factors in Table 1 of
BS 5400: Part 2 for Load Combination 1.

i. Serviceability limit state
    Moment due to dead load
    and superimposed dead load   = 776 kNm/m $= M_g$

    Moment due to HA load
    (HA udl + KEL)   = 497 kNm/m $= M_q$
    Total moment   = 1273 kNm/m

ii. Ultimate limit state
    Moment due to dead load
    and superimposed dead load   = 1048 kNm/m

    Moment due to HA load   = 683 kNm/m
   Total moment   = 1731 kNm/m

All moments are expressed /m width

6. **Stresses at serviceability limit state**

i.   Stress in existing structure due to permanent loads.
Modulus of elasticity for reinforcing bars,

$E_s = 200$ kN/mm²

Short term modulus of elasticity for concrete,

$E_c = 31$ kN/mm²

Long term value of E_c to allow for creep, E'_c

$E'_c = 0.5\ E_c = 15.5$ kN/mm²

Modular ratio, $m = \dfrac{200}{15.5} = 12.9$

Apply elastic analysis of `cracked' transformed

.mA $_{s1}$
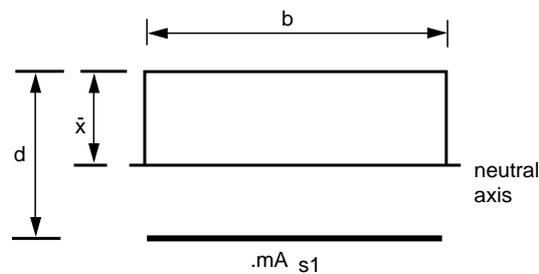
Where b = 1000 mm

d = 807mm, based on 30mm cover to reinforcement

A_{sl} = 6540 mm²/m width

(T25's in pairs at 150 centres)

Find $\bar{x}$, position of neutral axis

$$\frac{b\bar{x}^2}{2} - mA_{sl}\ (d - \bar{x}) = 0$$

$$\frac{10^3 \cdot \bar{x}^2}{2} - 12.9 \times 6540\ (807 - \bar{x}) = 0$$

$$\bar{x} = 294\ mm$$

Find Ic

$$\frac{b\bar{x}^3}{3} + mA_{sl}(d - \bar{x})^2 = I_c$$

$$10^3 \times \frac{294^3}{3} + 12.9 \times 6540 \times (807 - 294)^2 = I_c$$

$$I_c = 30.7 \times 10^9 \text{ mm}^4/m$$

Moment due to permanent loads, M_g

$$M_g = 776 \text{ kNm/m}$$

$\therefore$ Extreme fibre concrete compressive stress, σ_c

$$\sigma_c = \frac{M_g \, y_1}{I_c} \qquad \text{where } y_1 = \bar{x}$$

$$\sigma_c = \frac{776 \times 10^6 \times 294}{30.7 \times 10^9} = 7.4 \text{ N/mm}^2$$

Reinforcement tensile stress, σ_R

$$\sigma_R = \frac{776 \times 10^6 \times (807 - 294) \times 12.9}{30.7 \times 10^9}$$

$$\sigma_R = \underline{167.3 \text{ N/mm}^2}$$

ii.   Stresses in strengthened structure due to live load

        Considering live loads, only use short term value of modulus of elasticity for concrete, giving

        $m = 200/31 = 6.5$

        Apply elastic analysis to cracked transformed section neglecting any strengthening initially.

        $b = 1000$mm
        $d_1 = 807$mm
        $A_{sl} = 6540$mm^2/m

Find new value of $\bar{x}$

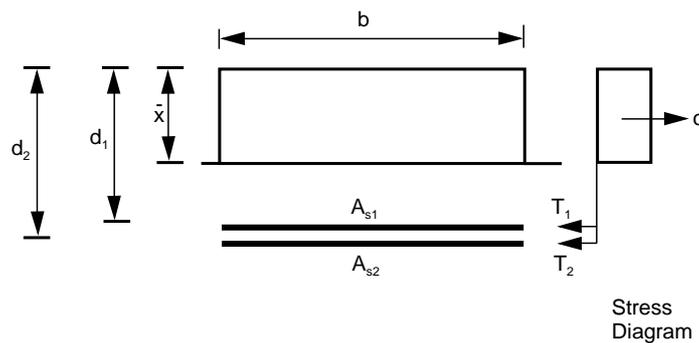$$\frac{10^3 . \bar{x}^2}{2} - 6.5 \times 6540 (807 - \bar{x}) = 0$$

$$\bar{x} = 223mm$$

Find new I_c

$$10^3 \times \frac{223^3}{3} + 6.5 \times 6540 (807 - 223)^2 = I_c$$

$$I_c = 18.2 \times 10^9 \text{ mm}^4/m$$

Recalculate $\bar{x}$ and I_c with strengthening plates bonded to concrete - try 5mm thick, 300mm wide steel

plate, width/thickness ratio = 60 (ref [11])

Stress
Diagram

To ensure all the slab is effectively reinforced the spacing of the plates should be such as to give a minimum overlap of L = 100mm at the top of the slab (see diagram).
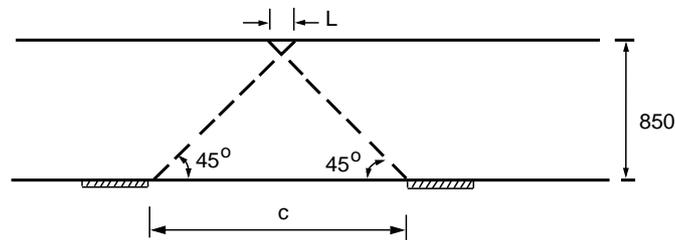
∴ Max clear distance between plates,
  c = [850 x 2] - 100 = 1600mm

∴ Taking one plate every 1.5m transversely
Area of steel plate, A_{s2} = 300 x 5/1.5
                    = 1000 mm²/m

Find new value for $\bar{x}$:

$$\frac{b\bar{x}^2}{2} - mA_{s1}(d_1 - \bar{x}) - mA_{s2}(d_2 - \bar{x}) = 0$$

$$10^3 \times \frac{\bar{x}^2}{2} - 6.5 \times 6540(807 - \bar{x}) - 6.5 \times 10^3(850 - \bar{x}) = 0$$

$$\bar{x} = 237mm$$

Find new value of I_c:

$$10^3 \times \frac{237^3}{3} + 6.5 \times 6540(807 - 237)^2 + 6.5 \times 10^3(850 - 237)^2 = I_c$$

$$I_c = 20.7 \times 10^9 \ mm^4$$

Increase in I_c due to strengthening is

$$= (20.7 - 18.20) \times 10^9 = 2.5 \times 10^9 \ mm^4$$

which gives a percentage of 13.7%

$$>12\% \therefore OK$$

Check combined stresses against max allowable in Table 2, BS 5400: Part 4

$$\sigma_c = 7.4 + \frac{497 \times 10^6 \times 237}{20.7 \times 10^9} = \underline{13.1 \ N/mm^2}$$

Max allowable $= 0.5 \ f_{cu} = 20N/mm^2 \therefore OK$

$$\sigma_R = 167.3 + \frac{497 \times 10^6 \times (807 - 237) \times 6.5}{20.7 \times 10^9}$$

$$\sigma_R = 256.3 \ N/mm^2$$

Max allowable $= 0.75 \ f_y = 345 \ N/mm^2 \therefore OK$

$$\sigma_{plate} = \frac{497 \times 10^6 (850 - 237) \times 6.5}{20.7 \times 10^9} = 95.7N/mm^2$$

Max allowable $= 150 \ N/mm^2 \quad \therefore OK \ (Section \ 3.5)$

7. **Shear stress in adhesive layer**

Allow for strengthening plates over 80% of the span, ie to within 1.65m of supports.

Shear force at plate ends due to live load at the ultimate limit state, V = 138 KN/m.

Elastic longitudinal shear stress at plate ends, $q = \dfrac{VA\overline{y}}{I\,b}$

where

$\qquad A\overline{y} = mA_{s2}\,(d_2 - \overline{x}) = 6.5 \times 10^3\,(850 - 237)$

$\qquad A\overline{y} \quad = 3.98 \times 10^6\ \text{mm}^3$

and $\qquad b \quad = 300\ \text{mm} \equiv 200\ \text{mm of plate/metre}$

$\qquad \therefore q \quad = \dfrac{138 \times 10^3 \times 3.98 \times 10^6}{20.7 \times 10^9 \times 200} = 0.1\ \text{N/mm}^2$

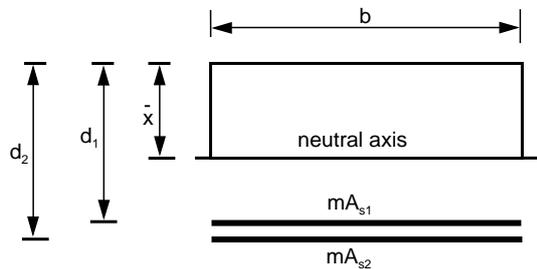Check allowable ultimate longitudinal shear stress $v_l{}^*$ in concrete, grade 40;

$\qquad v_l = 0.8\text{N/mm}^2$ - shear plane in concrete

$\therefore$ The design is satisfactory assuming the bond strength of the adhesive exceeds the permissible shear stress in the concrete.

* Table 31, BS 5400, Part 4

8. **Section capacity at ultimate limit state**

i. Resistance moment*

For equilibrium in section

$\qquad T_1 + T_2 = C$

$\qquad A_{s1}\,f_{s1} + A_{s2}\,f_{s2} = 0.4\,f_{cu}\,b\overline{x}$

At ultimate limit state

$\qquad f_{s1} = 0.87f_{yl} \quad \& \quad f_{s2} = 252\text{N/mm}^2\ (265/1.05)$

$\therefore 6540 \times 0.87 \times 460 + 10^3 \times 252 = 0.4 \times 40 \times 10^3 \times \overline{x}$

$\qquad \therefore \overline{x} = 179\text{mm}$

Ultimate moment of resistance $= M_u$

Where $M_u = 0.4 \, f_{cu} \, b\bar{x} \, (d_1 - \bar{x}/2) + 252 \, A_{s2} \, (d_2 - d_1)$

$M_u = 0.4 \times 40 \times 10^3 \times 179 \, (807 - 179/2) + 252 \times 10^3 \times (850 - 807)$

$\therefore \underline{M_u = 2066 \text{kN-m}}$

Compare with total moment M (from 5ii.)

$\underline{M = 1731 \text{ kN-m}} \qquad \therefore \text{ OK}$

$M_u > 1.15 \, M$

*Clause 5.3.2.1 BS 5400: Part 4

ii. Shear resistance (BS 5400: Part 4 Cl 5.4.4)

Neglecting the strengthening plates,
Shear stress in slab $v = \dfrac{V}{bd_1}$

$v = \dfrac{462 \times 10^3}{10^3 \times 807} = \underline{0.57 \text{ N/mm}^2}$

Find ultimate shear stress v_c from Table 8, Part 4

$\dfrac{100 \, A_s}{bd_1} = \dfrac{100 \times 6540}{10^3 \times 807} = 0.81$

for $f_{cu} = 40$
$\qquad v_c = 0.68 \text{ N/mm}^2$

allow for depth factor ξ_s from Table 9, Part 4

$\xi_s \, v_c = 0.90 \times 0.68 = \underline{0.61 \text{ N/mm}^2}$

$\therefore \; v < \xi_s \, v_c \;$ shear capacity is OK

9. **Plate details**

An assumed width/thickness b/t value of 60 gives an effective anchorage length/width l_a/b of 1.2   (ref [11])

    $\therefore\ l_a = 1.2 \times 300 = 360$ mm

i.   Anchorage bolts at plate ends (ref [6])
    Determine number of anchor bolts required for plate ends, based on bolts resisting 3 times the ultimate shear stress at the plate ends. (See Section 7).

        Shear force to be resisted by bolts within anchorage zone,

            $= 3 \times q \times A_{s2} = 3 \times 0.1 \times 360 \times 300 \times 10^{-3}$

            $= 32.4$ kN

        Number of bolts required will depend on the capacity of fixing into the substrate.

ii.   Plate overlap lengths

        For a b/t of 60 plate overlaps ≮ 400mm   (ref [11]).

        If a maximum plate length for handling = 6m (71kg)

        No of plates required = 3 x 4.4m lengths

       $\therefore$ Require 2 bonded cover plates to transfer load between lengths.