Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 37 (1982)

Artikel: Fatigue performance of adhesive bonded joints for bridge deck construction

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DOI: https://doi.org/10.5169/seals-28934

Fatigue Performance of Adhesive Bonded Joints for Bridge Deck Construction

Résistance à la fatigue d'assemblages collés pour la construction du tablier des ponts

Ermüdungsfestigkeit geklebter Verbindungen für den Bau von Brückenfahrbahnplatten

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SUMMARY
This paper describes numerous laboratory tests in fatigue which have been carried out on adhesive bonded open sandwich beams and slabs and on adhesive bonded steel/steel lap joints both before and after being subjected to various potentially adverse treatments. A good joint has been shown to possess excellent fatigue properties, superior to many details in welded steel. Research is now in hand to investigate the potential benefit of adhesive bonded web stiffeners in place of the conventional, fatigue prone, welded or bolted connections.

RESUME
Cet article décrit de nombreux essais de fatigue effectués en laboratoire sur des poutres et dalles mixtes, béton-tôle d'acier, dont la connection est réalisée par collage, ainsi que sur des assemblages collés acier-acier avec plaque de recouvrement. Les essais ont été soumis avant et après collage à des traitements potentiellement défavorables. Un bon assemblage a été remarqué possédant d'excellentes qualités d'endurance, supérieures à bien des détails en acier soudés. La recherche est maintenant à même d'étudier les avantages potentiels des raidisseurs collés au lieu des assemblages conventionnels, soudés ou boulonnés, de faible endurance.

ZUSAMMENFASSUNG
Der Bericht beschreibt zahlreiche Laborversuche an geklebten Bauteilen unter Ermüdungsbeanspruchung. Balken und Platten in geklebter Verbundbauweise sowie zweischnittige geklebte Stahlverbindungen sind untersucht worden. Die Prüfkörper wurden vor den Versuchen verschiedenen ungünstigen Umgebungseinflüssen ausgesetzt. Es wurde festgestellt, dass gut ausgeführte Verbindungen ausgezeichnete Ermüdungsfestigkeiten aufweisen, die diejenigen vieler geschweisster Details übertreffen. Die Forschungsarbeiten sind soweit gediehen, dass jetzt die möglichen Vorteile geklebter Stegsteifen gegenüber den geschraubten oder geschweissten untersucht werden können.

1. INTRODUCTION

The use of a conventional reinforced concrete slab is a common method of forming the roadway deck of medium span bridges. In longer spans the self weight forms a greater proportion of the total load, and a welded steel orthotropic deck becomes more economic. The "open sandwich" and "inverted catenary" decks described by SMITH & CUSENS [1] are both lighter than conventional reinforced concrete and cheaper than a welded steel deck. The open sandwich slab has a uniform thickness of concrete bonded to a flat mild steel plate. In the inverted catenary type the plate is curved to form a shallow arch. In both types the connection between steel and concrete is made with epoxy resin adhesive. The slabs are being developed for factory precasting.

Structural developments applied to bridges must remain sound when exposed to cyclic loading and to extremes of temperature for many years. The extensive programme of research carried out in the Wolfson Bridge Research Unit into adhesive bonded joints and their application to these decks has been summarised by MAYS & SMITH [2]. The present paper describes the fatigue testing of joints which forms part of the overall programme. Much of the fatigue testing for slabs has been carried out on small scale open sandwich beams but some half scale and full scale slabs have been tested. The fatigue performance of epoxy resins in shear has also been investigated using large numbers of double shear steel to steel lap joints. The results of these tests have led to work on adhesive bonded stiffeners for steel plates.

2. OPEN SANDWICH BEAMS

2.1 Specimen Manufacture

Beam specimens were 26 mm wide by 344 mm long with 17.2 mm of concrete on a 0.6mm steel plate. This represents, to a scale of approximately 1:6, a transverse strip from an open sandwich slab in a composite bridge. Steel plate, cut to size, was degreased by washing with detergent, rinsed with tap water and dried in warm air. Mill scale was removed with a mechanical sander and the surface was hand roughened with emery. Approximately 1 mm of adhesive was applied to the steel. Ordinary portland cement concrete with 5 mm maximum size aggregate was placed on the fresh adhesive and compacted on a vibrating table. The beams were demoulded after 24 hours and cured for 27 days at 20^{o}C and 95% relative humidity.

The adhesives used were:
- (1) XD800; a thixotropic paste mixed with 10% of its own weight of liquid hardener understood to be an aliphatic polyamine;
- (2) AV100 + HV100; a high viscosity liquid resin mixed with its own weight of polyamide hardener;
- (3) AY105 + HY953F; a liquid resin mixed with its own weight of polyamide hardener;
- (4) XD548 + HY941; a pigmented paste mixed with half its own weight of medium viscosity liquid hardener understood to be an aromatic polyamine.

All are two part cold cure epoxy resins supplied by Ciba-Geigy Ltd.

2.2 Fatigue Testing

After curing, three beams made with each of adhesives 1,2 and 4 were subjected to control fatigue tests in four point bending on a span of 310 mm (Fig. 1). The loads were applied symmetrically 52 mm apart. Constant amplitude sinusoidal load cycles were applied at a frequency of 15 Hz. The minimum load in each cycle was 10% of the maximum. Beams which survived 1.5 million cycles were later tested in static flexure.

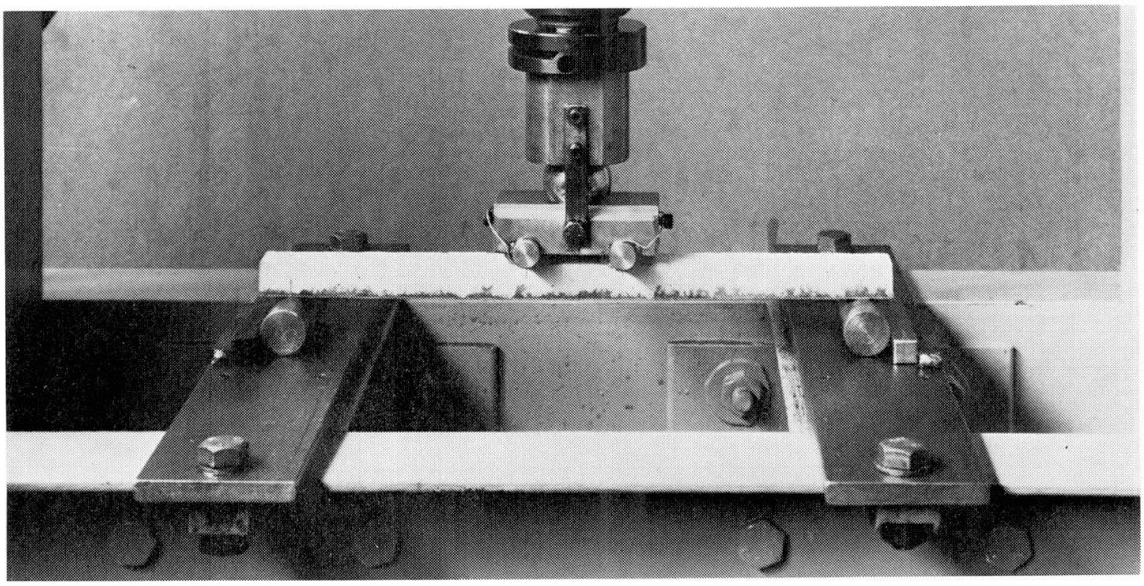

Figure 1 Open sandwich beam under test

A further nine beams for each adhesive were waterproofed with a coating of paraffin wax on all but their top surface and subjected to one of the following treatments:
- (1) continuous immersion in tap water for 8 weeks;
- (2) wetting in tap water for 6 hours twice weekly for 26 weeks;
- (3) as 2 but in 3% w/w salt solution.

These treatments were more adverse than that used on similar specimens reported by CUSENS & SMITH [3]. At the end of the treatment period, these beams, together with others which had been stored in the laboratory for the same period, were fatigue loaded in a similar manner to that described for the controls. Further beams have been stored for later treatment.

Reliable specimens could not be made with adhesive (3) and tests were abandoned after completing the study of treatment (1).

2.3 Results and Discussion

The results of the fatigue tests are presented in Figure 2. They are superimposed on the mean stress range versus endurance curves for grade 50 steel from BS5400 part 10 [4] plotted on log log scales with the stress range expressed as a fraction of the static (yield) strength.

Control beams with adhesive (1), (2) or (4) performed better than a class B welded detail. No significant deterioration took place during 32 weeks storage in the laboratory. Beams made with adhesive (1) deteriorated to class D after treatment (1) and had little strength after treatments (2) or (3). Those made with adhesives (2) or (3) showed poor resistance to fatigue after any of the treatments. These two adhesives had similar hardeners. In all these specimens rust was found on the steel plate after testing. The appearance of the rust suggested that aggregate particles had penetrated the adhesive layer, probably during compaction. In beams made with adhesive (4) aggregate penetration of the adhesive was also apparent, but corrosion was not significant at the time of testing. These beams still had high fatigue strength after treatments (1), (2) or (3).

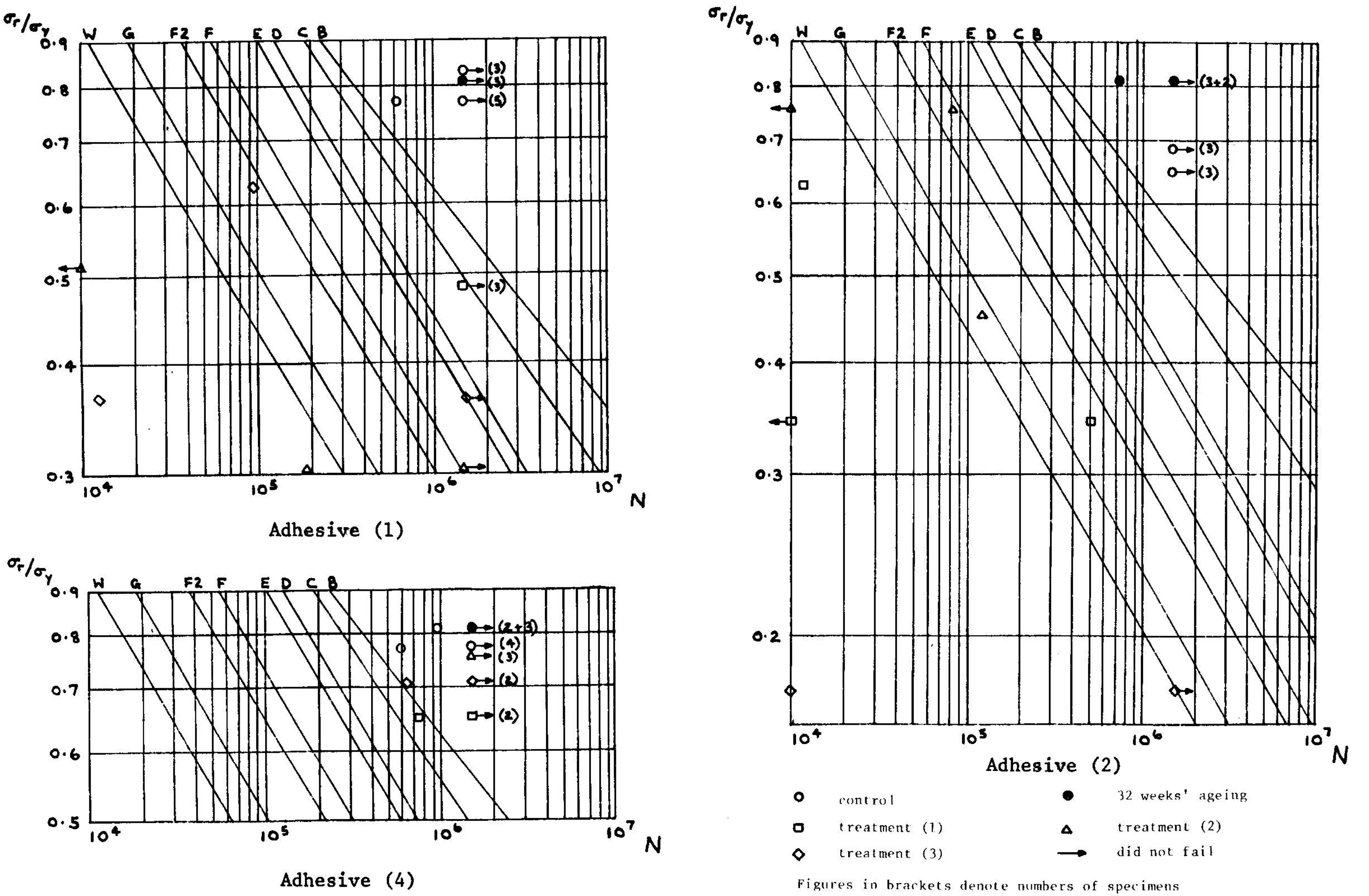

Figure 2 Fatigue test results for open sandwich beams

Work is now in progress using beams with two layers of adhesive (4), the first of which is allowed to harden prior to casting. Fatigue results to date for control beams and after treatment (2) are all superior to a class B detail. There is little, if any, evidence of rusting and no tendency for separation between the layers.

3. OPEN SANDWICH SLABS

The performance of open sandwich slabs under traffic is being monitored over a period of years. A 2 m square slab has recently been installed in a test pit in Dundee's outer peripheral trunk road. Two half scale models have been tested in fatigue in the laboratory by applying patch loads at various positions on each slab. Each slab survived 7.5 million cycles of 28 kN load, and only failed after at least a further 1.7 million cycles at loads of up to 2.5 times this value. The shear failure mode was similar to that observed in static test.

4. STEEL TO STEEL LAP JOINTS

CUSENS & SMITH 3 reported fatigue test results for steel to steel double lap shear joints with adhesives 1, 2 and 4 after curing at room temperature, 40°C and 80°C. Further fatigue tests have been carried out on similar joints with different steel surface preparations.

4.1 Specimen Manufacture and Testing

Bright steel bar 25.4 mm x 5 mm was butt jointed with two 80 mm long cover plates of the same section. Bonding surfaces were cleaned of rust, degreased with acetone and blasted with metal grit to a finish resembling Swedish Standard ASa 2½ [5]. Three variations of steel surface condition were used to ascertain the effect of imperfect preparation on fatigue performance. The surfaces were:

- (1) standard clean rough surface as described;
- (2) as (1) but blasted with grade 50 sand to give a clean smooth surface resembling ASa 3 [5]:
- (3) as (1) but with cover plates allowed to rust over 15% of their area.
- (4) as (1) but cover plates dipped in 5% w/w salt solution to produce rust over 20% of their area after 20 hours.

The joints were assembled in a jig to give a glue line thickness of 0.65 mm. The ends of the main bars were debonded to eliminate direct stress transfer. Some specimens were heated at 15°C per hour then cured at elevated temperatures for 24 hours before being allowed to cool slowly. The specimens were then gripped in mechanical wedge grips (Fig. 3) and cycled under load control with a sine wave form at a frequency of 15 Hz. The minimum load in each cycle was 10% of the maximum. Specimens which survived 1.5 million cycles were tested at progressively higher loads until failure.

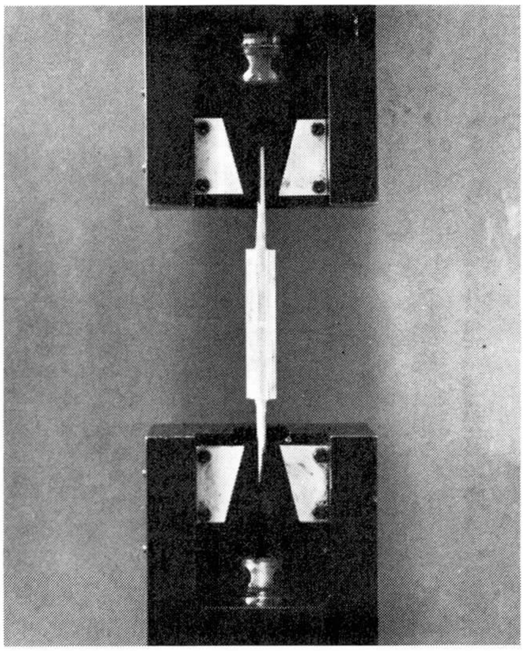

Figure 3 Lap joint under test

4.2 Results and Discussion

Results of fatigue tests on lap joints with the standard surface (1) are summarised in Table 1.

Adhesive	Curing Temp.	Mean shear stress range		Endurance (cycles)
		N/mm^2	as % static strength	
(1)	Room temp.	5.8	4.5 - 45	321,357
	80°C	6.4	4 - 40	307,653
(2)	Room temp.	5.2	4 - 40	388,075
	80°C	7.3	4 - 40	835,487
(4)	Room temp.	5.5	5 - 50	Survived 1,500,000
		7.7	7 - 70	29,700
	80°C	5.6	5 - 50	Survived 1,500,000
		7.8	7 - 70	18,357

Table 1 Endurances for lap joints

Static strength was reduced with surface conditions (2), (3) and (4) by up to 20% for adhesive (1) and 12% for adhesive (2). Adhesive (4) attained 83% of its control strength on surfaces (3) and (4) but only 53% on the smoother surface (2). All specimens were tested in fatigue at the proportion of their static strength indicated in Table 1. No reduction in endurance was noted for any group. All results are the mean for three tests.

Testing at controlled temperatures between -25°C and + 55°C is now in progress at endurances of up to 100 million cycles. Control results for adhesive 1 show no loss of fatigue strength at temperatures between -25°C and 45°C. A dramatic loss of fatigue strength was found at + 55°C. Specimens with all four adhesives are ageing in a variety of environments before testing and further results will be published shortly [6].

5. FATIGUE SUSCEPTIBLE DETAILS IN WELDED STRUCTURAL STEELWORK

The good fatigue resistance of the steel to steel lap joints described above suggested the use of adhesives in steel fabrications where stresses were low but fatigue damage was a serious problem. The most promising application is in the attachment of stiffeners to girder webs. The stress in these connections is usually low but welding seriously reduces the fatigue strength of the main material. The alternative bolted connection exhibits better fatigue resistance but reduces the area of metal available to carry direct stress. A preliminary study using the adhesives described above in specimens as shown in Figure 4 indicated that, although a saving was available, a different adhesive formulation would be required, possibly combined with a redesigned joint.

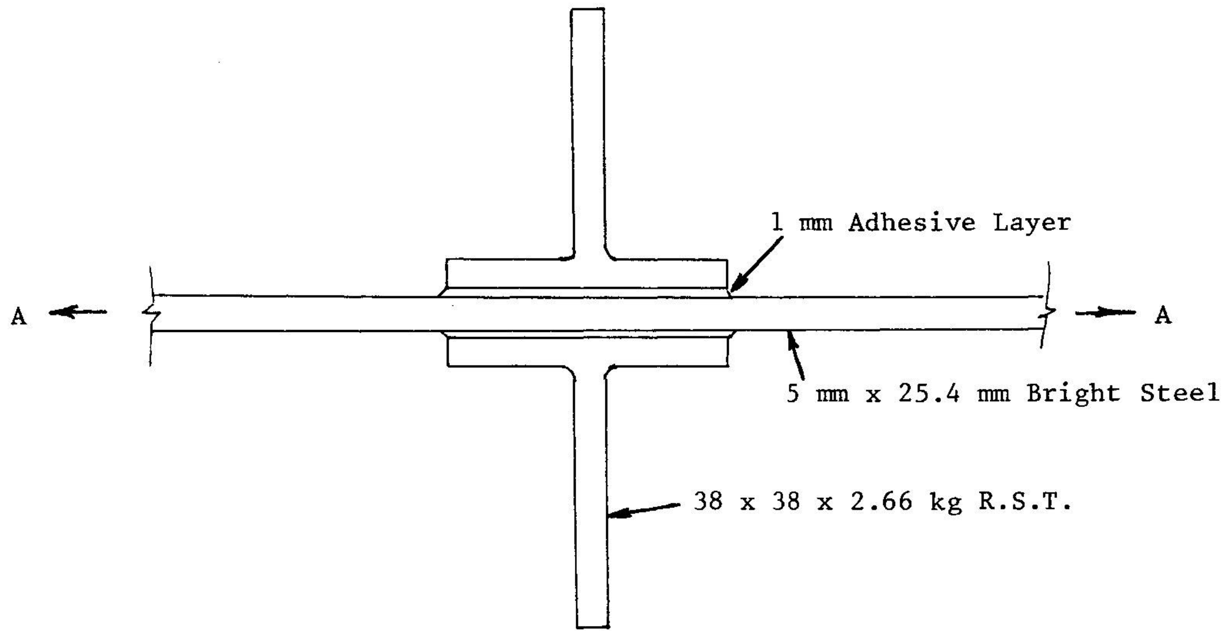

Fig 4. Test Specimen. Adhesive Bonded Unstressed T

5.1 Choice of Adhesive

The different elastic properties of steel and adhesive ensure that even small notionally unstressed attachments bonded to stressed steel result in long joint effects in the adhesive. Of the materials so far considered Permabond ESP105 exhibits the best static strength and fracture toughness. It also seems less susceptible to imperfect surface preparation than some others. Its high fracture toughness makes it resistant both to the long joint shear stresses mentioned above and to the cleavage or peel stresses likely to be induced by accidental damage to the attachment. A disadvantage of this adhesive is the need to cure at elevated temperatures, though 100 to 150°C should be readily achievable in fabrication shops where preheating for welding is common.

5.2 Test Methods

Specimens as shown in Figure 4 were first subjected to cyclic loading in tension in direction A. The attachments were then pulled off, by gripping the outstand of the Ts, to indicate residual strength and to allow inspection of any cracks induced by fatigue.

5.3 Results

The preliminary tests indicate that with stress ranges up to 100 N/mm^2 in tension in the main material, glue lines up to 40 mm long remain undamaged after 3.5 million cycles. At a stress range of 130 N/mm^2 fatigue damage is significant after 1 million cycles.

A substantial test programme is now in hand. This will include flexural loading of girders with adhesive bonded stiffeners. The search for suitable adhesives continues.

6. ACKNOWLEDGEMENTS

The work described here was carried out in the Wolfson Bridge Research Unit, director Professor A.E. Vardy, with financial assistance from the Science & Engineering Research Council and the Transport & Road Research Laboratory. The majority of the experimental and theoretical work was undertaken by the following students: G. Ching, L.M. Goh, K.C.G. Ong.

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