Efficacy of Different Materials and Methods of Repair in Highway Bridges

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ABSTRACT

Repairs were carried out on three highway bridges using repair materials of higher elastic modulus than the substrate, $E_{rm}>E_{sub}$ and materials with $E_{rm}<E_{sub}$. Three methods of repair application were adopted: hand applied patch repair, sprayed repair and flowing repair application. Members of the bridge structures were repaired in the propped and unpropped states. It is shown that repairs using materials with $E_{rm}>E_{sub}$ perform efficiently. Hand applied repairs act as cosmetic repairs with no significant load transfer. Application of repair to propped structures leads to unpredictable stress redistribution in the long-term.

INTRODUCTION

Recent research of the authors [1-6] has revealed significant limitations to the repair specifications and practice procedures adopted by the bridge infrastructure owners, managers[7] and the concrete repair industry[8-9]. There is limited quantitative understanding of the effect of material property mismatch on the long term interactions which occur between the repair patch and the substrate concrete. These interactions will have a marked influence on restrained shrinkage cracking in the repair material and long-term external load transfer from the substrate[5]. Consequently these effects will influence greatly the choice of optimum materials and methods of repair application.

TEST PROGRAMME

Repairs were carried out on three highway bridges on lateral beams supporting the bridge deck, on bridge abutments and on columns and piers. Different formulations of commercial repair materials were used, representing a wide range of material properties (strength, elastic modulus, shrinkage and creep). Three methods of repair application were adopted: hand applied repair patches, sprayed repairs using the dry gunite process, repairs by placing flowing materials in watertight formwork. The repair patches were instrumented extensively with vibrating wire gauges and data loggers to record long-term strain distribution in different phases of the repair patches: substrate, reinforcement, repair material.

Gunthorpe Bridge

Gunthorpe bridge is a three span reinforced concrete arch bridge spanning the River Trent at Gunthorpe, Nottinghamshire. It was built in 1927 to replace an old iron toll-bridge. Reinforcement corrosion had resulted in high degree of deterioration in the bridge members. Repairs were carried out to the lateral beams spanning between the arch ribs (Figure 1) and to three areas on the South abutment measuring approximately 2.3m x 1.8m. The bridge was repaired in an unpropped state.

The lateral beams were repaired with hand applied patch repairs. Deteriorated concrete was removed along the soffit of the beam to a total depth of 130-140mm (up to 25mm behind the steel reinforcement). The exposed steel was grit blasted and then primed. Vibrating wire gauges (surface and embedment) were attached to the repair patches as shown in Figure 2 to monitor long-term strains. Figure 3 shows the hand applied repair to the beams.

The repair patches to the abutment were applied by spraying, using the dry spray process. The average depth of the repair patch was 140mm. The vibrating wire gauges were attached as shown in Figure 4 - one gauge was attached to the substrate at the interface of repair, one was attached to the longitudinal reinforcement bar and one was embedded in the repair material in the plane of the longitudinal reinforcement bars.

Lawns Lane Bridge

Lawns Lane bridge is a three span reinforced concrete bridge which carries the M1 near Wakefield. It is a 1960's structure which required substantial repairs to the abutments and the North piers. Figure 5 shows the locations of repairs to the North abutment. The repairs were applied to a depth of approximately 140mm using the dry spray process. Vibrating wire gauges were attached as shown in Figure 4. The repairs were carried out in an unpropped state.

Sutherland Street Bridge

Sutherland Street bridge carries the B6080 over an access road which once linked steel industries in Sheffield. The superstructure consists of an in-situ deck supported by prestressed beams. The substructure consists of reinforced concrete beams and columns in a portal frame configuration. Repairs were carried out to the beams and columns of the portal frame (substructure) as shown in Figure 6. The repairs were applied using the flowing material method of application. Half of the North frame of the bridge was maintained in an unpropped state during the application of repair. The remaining bridge (the South frame and the remaining half of the North frame) was maintained in a propped state during the application of repair. Propping remained in place for approximately 28 days after the application of repair.

The deteriorated concrete was removed to a depth of 25mm behind the reinforcement. The exposed steel was grit blasted and primed. Plywood shuttering was used for the flowing repairs. The substrate concrete was saturated by filling the shuttering with water and leaving in place overnight. The flowing repair material was poured into the shuttering from a bucket. Compaction was achieved by tapping the shuttering with a wooden hammer as the material was poured. Shuttering was left in place for at least three days after the pour. Vibrating wire strain gauges were attached in a similar manner to the previous bridges on the substrate at the repair interface, on the steel reinforcement and embedded in the repair material in the plane of the reinforcing bars.

Repair Materials

Properties of the materials used in the bridge repairs are given in Table 1. Three materials (G1, G2 and G3) were used at Gunthorpe bridge for the dry spray application. G1 and G2 are commercial materials; G3 is a mixture of conventional sand and cement. Spray repairs were applied by an independent specialist contractor. Commercially produced hand applied repair materials G4, G5 and G6 were used at Gunthorpe bridge. Five commercial materials (L1 to L5) were applied at Lawns Lane bridge using the dry spray process. L1 was the only material which fully complied with the requirements of the Highways Agency Repair Specification BD 27/86. Repairs to Sutherland Street bridge used the flowing materials technique. Three commercially produced flowing materials S1-S3 were used. The fourth material, S4 was a laboratory designed conventional flowing concrete incorporating a superplasticiser and polypropylene fibres.

RESULTS AND DISCUSSION

Performance of High Stiffness Repairs ($E_{rm}>E_{sub}$)

The typical long-term strains monitored in the repair patches on the abutments at Lawns Lane and Gunthorpe bridges are plotted in Figure 7. Repairs were applied to unpropped members. Repair materials of elastic modulus, E_{rm}, greater than that of the substrate, E_{sub}, are considered. Strains in the substrate at the repair interface, in the steel reinforcement and in the repair material (in the plane of the longitudinal reinforcement) are plotted. A simplified schematic representation of the strain-time relationship is made in Figure 8 in which the strains monitored by the reinforcement gauge and the embedment gauge in the plane of the reinforcement are averaged. Figure 8 clearly identifies four stages (zones) of strain (and, therefore, stress) transfer. Stage 1 represents the shrinkage strain transfer from the stiffer repair material ($E_{rm}>E_{sub}$) into the substrate concrete at the interface and into the steel reinforcement. The degree of shrinkage transfer is a function of E_{rm}/E_{sub} and the free shrinkage characteristics of the repair material(5) . Zone 2 is a steady state condition of strain (and, therefore, stress) transfer which occurs after the repair material shrinkage stabilises. Zone 3, from week 25 to 47, represents the long-term effects of load redistribution from the substrate structure into the repair patch(5). The long-term load distribution from the substrate is effective in neutralising the tension in the repair material caused by restrained shrinkage.

Performance of Low Stiffness Repairs ($E_{rm}<E_{sub}$)

A representative example of long-term strain distribution in repairs with low stiffness materials ($E_{rm}<E_{sub}$) is presented in Figure 9. Spray applied repairs to unpropped bridge abutments are considered. Figure 9 does not identify any of the zones of strain transfer which are evident for high stiffness repair materials ($E_{rm}>E_{sub}$) in Figures 7 and 8. Low stiffness repair materials ($E_{rm}<E_{sub}$) are ineffective in transferring shrinkage strain to the substrate and, therefore, sustain higher degrees of restrained shrinkage tension. Consequently, low stiffness repairs are prone to cracking as evident in Figure 10.

Performance of Flowing Material Repairs, $E_{rm}>E_{sub}$

Figure 11 shows the long-term strain distribution in the repair patch of a flowing material applied to an unpropped compression member. The figure shows a well defined shrinkage transfer stage followed by a steady state. A long-term external load redistribution stage is not identified (Zone 3) as in the case of spray applied repairs to unpropped members.

The application of flowing repairs to propped compression members was also considered. The removal of propping after the 28 days of repair application was found to cause a 'disturbance' in the load distribution by introducing new non-uniformities of loading. This results in an erratic stress redistribution in different phases and the effects of shrinkage transfer and other zones of strain transfer, as in Figure 8, cannot be detected.

Cosmetic Repairs, $E_{rm}<E_{sub}$

Hand applied repairs to the very heavily reinforced lateral deck beams at Gunthorpe bridge (Figure 1), using repair materials of $E_{rm}<E_{sub}$ (Table 1), resulted in cosmetic repairs. A strain-time plot of the strain gauges attached at different locations of a beam (Figure 2) is shown in Figure 12. The strain-time plots of different beams showed no clear and consistent pattern of strain distribution in the different phases of the repair patch. There was little interaction between the substrate beam and the repair patch; no significant load transfer from the substrate to the repair was evident in the long term.

CONCLUSIONS

The following conclusions are drawn from the results presented in the paper.

1 Efficient repairs are achieved with high stiffness materials i.e. $E_{rm}>E_{sub}$. Effective strain (therefore, stress) transfer is possible during the shrinkage stage and long-term load transfer from the substrate.

2 Low stiffness repairs i.e. $E_{rm}<E_{sub}$ result in ineffective strain (and stress) transfer and are prone to cracking.

3 Flowing repair materials are effective in transferring shrinkage strain to the substrate when $E_{rm}>E_{sub}$. Long term redistribution of load from the substrate structure does not take place.

4 Repairs to propped structures result in unpredictable strain (and stress) distribution in the long-term after the removal of propping.

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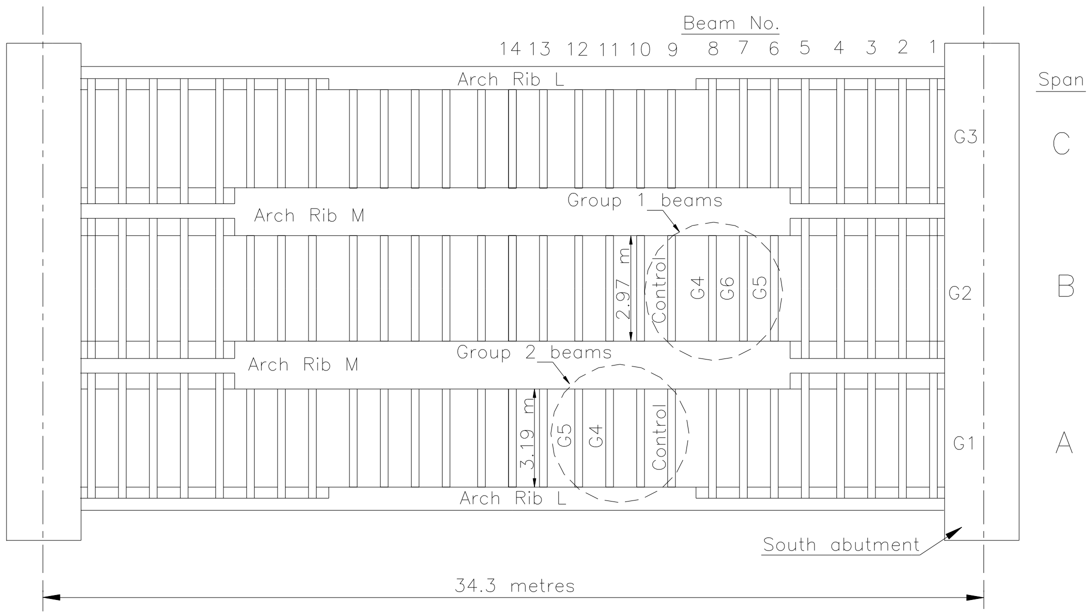

Figure 1: Lateral beams at Gunthorpe Bridge repaired with hand applied materials

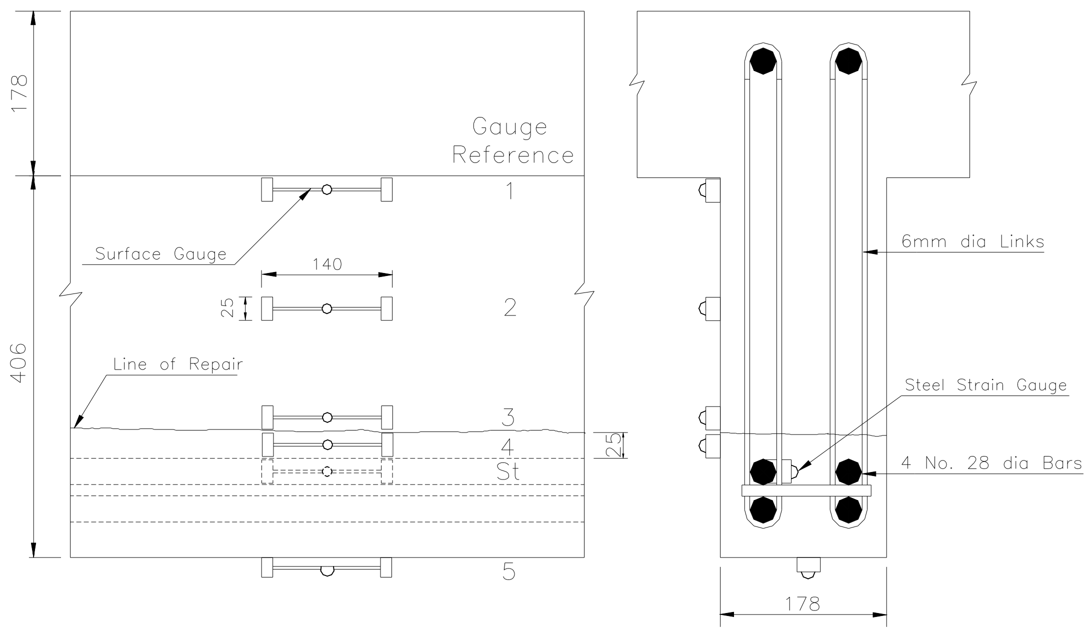

Figure 2: Position of vibrating wire strain gauges in the beams at Gunthorpe Bridge

Figure 3: Hand applied repairs to beams at Gunthorpe Bridge (unpropped structure)

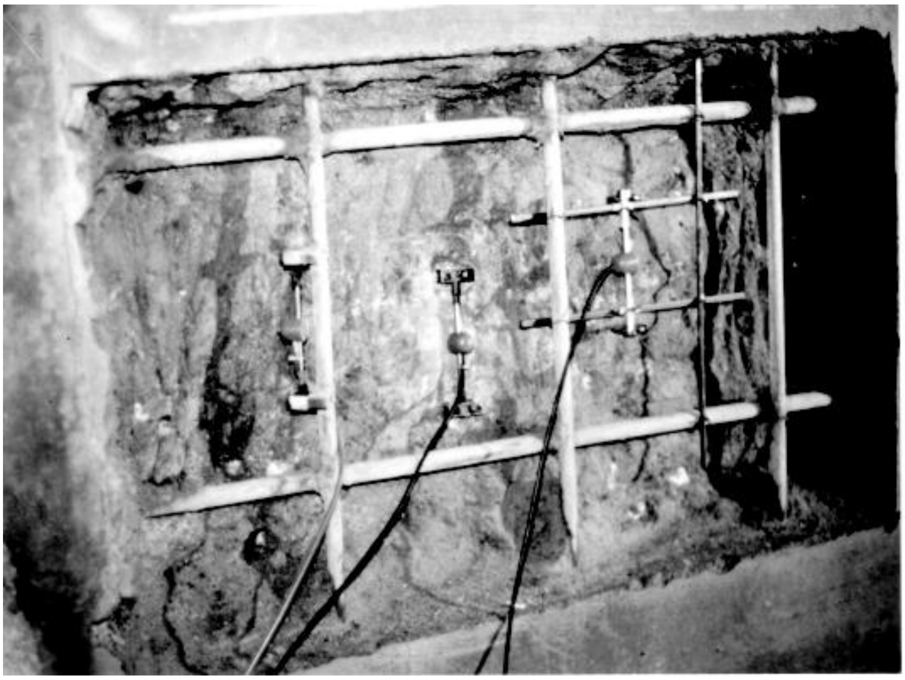

Figure 4: Location of vibrating wire strain gauges in the repair patches of bridge abutments

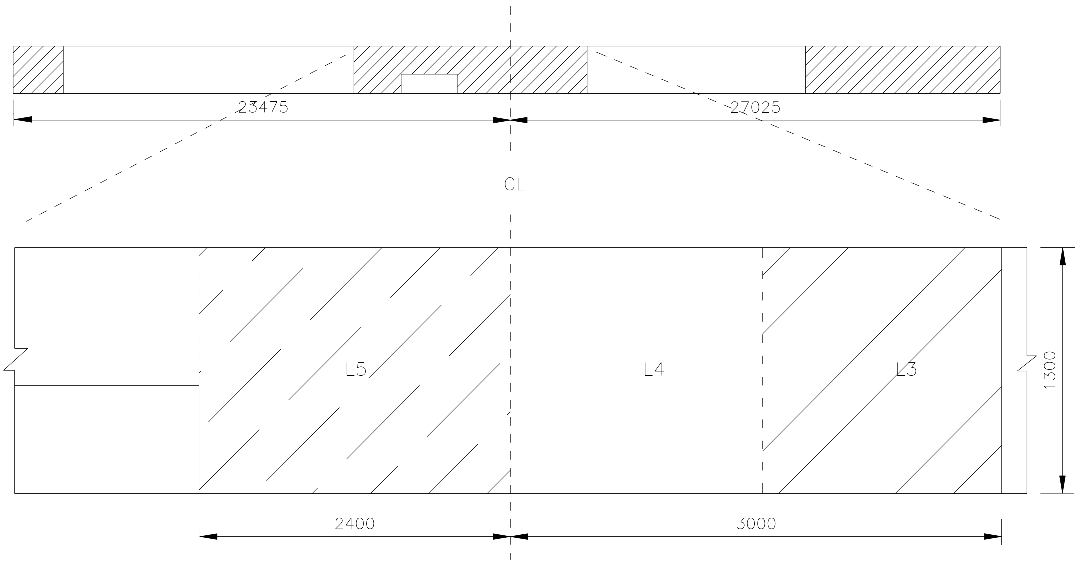

Figure 5: Location of spray applied repair patches on the north abutment, Lawns Lane Bridge (unpropped structure)

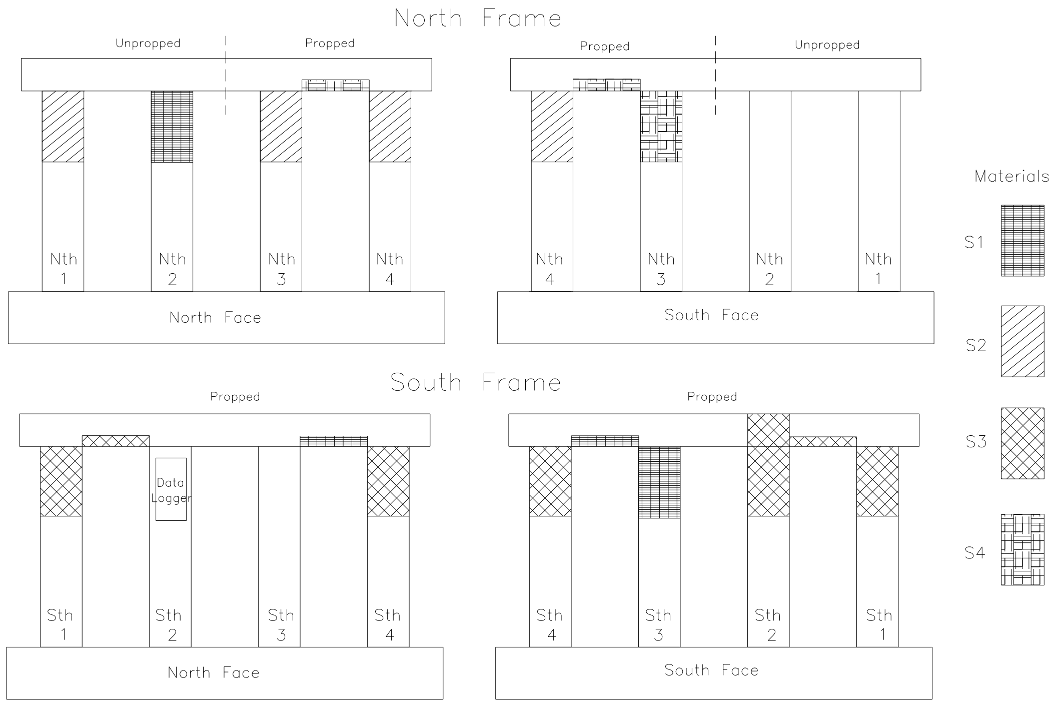

Figure 6: Location of flowing repairs at Sutherland Street Bridge (propped and unpropped members)

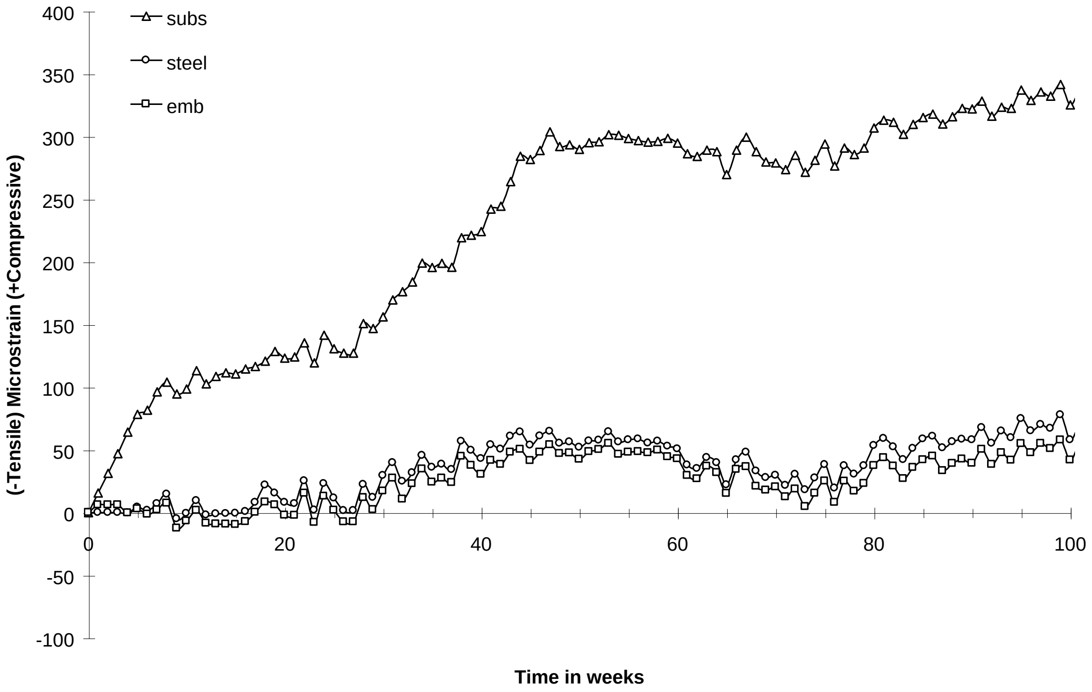

Figure 7: Long-term strain distribution in repair patch. $E_{rm} > E_{sub}$. Lawns Lane Bridge abutment. Sprayed repairs

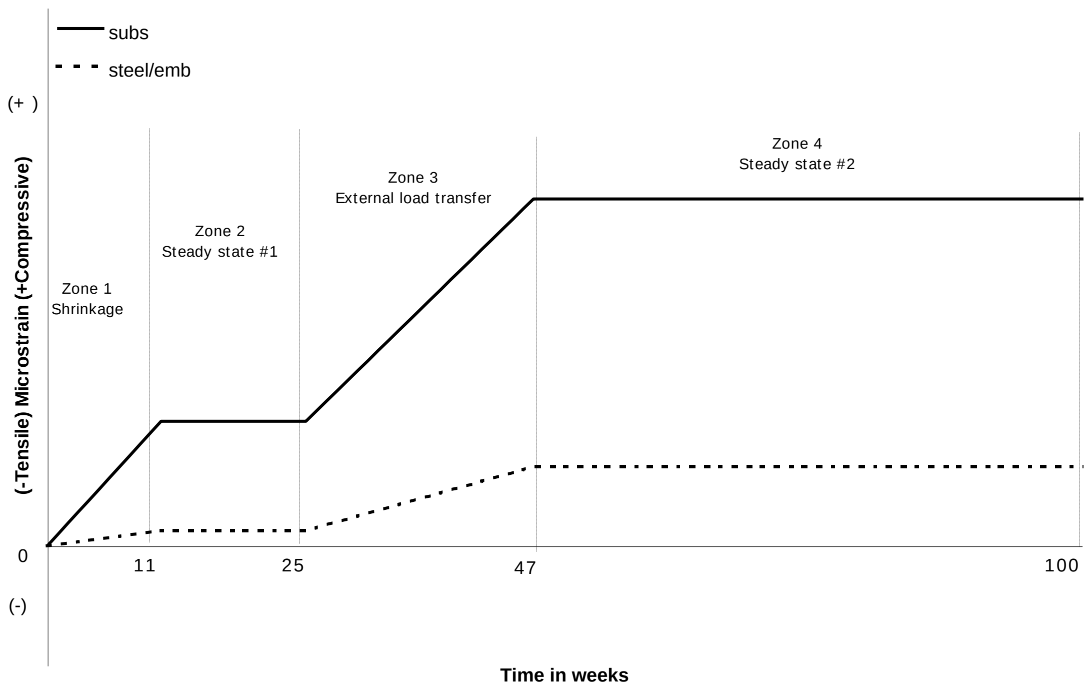

Figure 8: Schematic strain-time relationship within a repair patch. $E_{rm} > E_{sub}$.

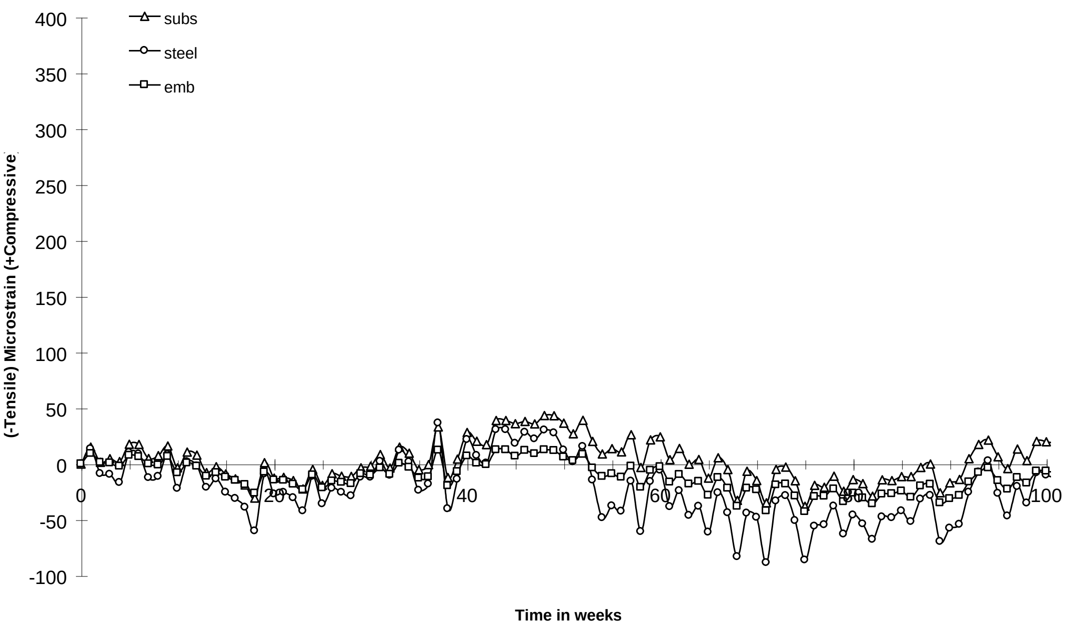

Figure 9: Long-term strain distribution in repair patch. $E_{rm} < E_{sub}$. Gunthorpe Bridge abutment. Sprayed repair

Figure 10: Restrained shrinkage cracking in repair patch. $E_{rm} < E_{sub}$.

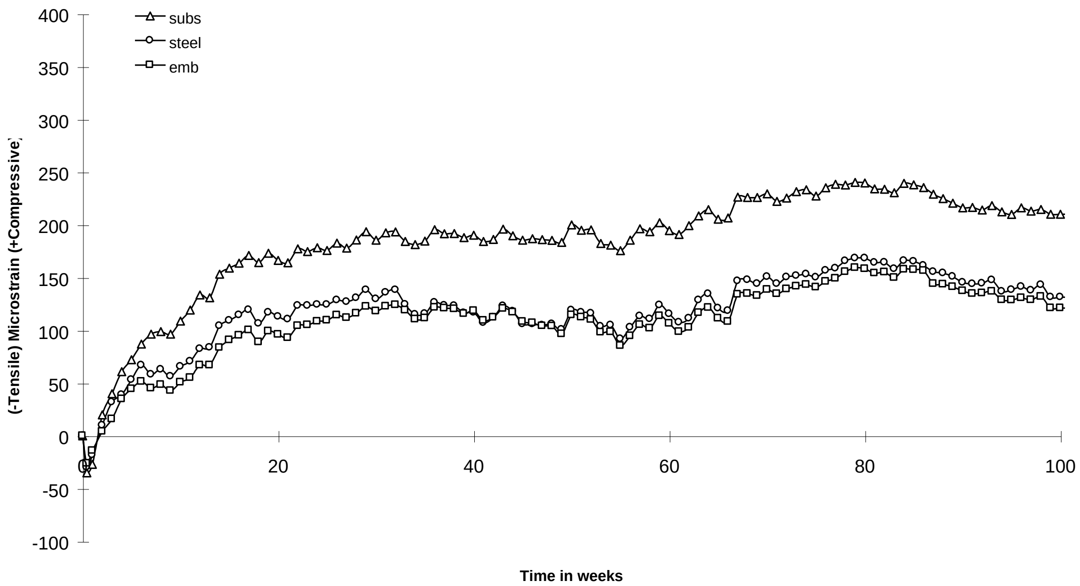

Figure 11: Long term strain distribution in repair patch. $E_{rm} > E_{sub}$. Sutherland Street Bridge column. Flowing repair.

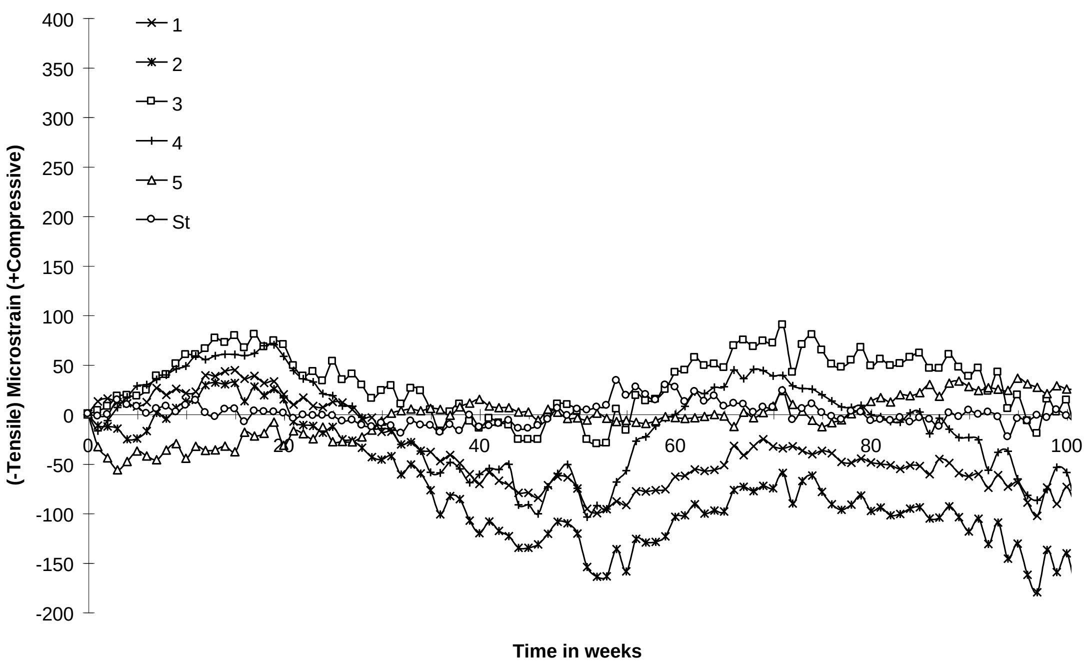

Figure 12: Long term strain distribution in the repairs to bridge beams at Gunthorpe Bridge. $E_{rm} < E_{sub}$.

Table 1: Properties of Repair Materials and Substrate Concrete

Bridge	Material	Application	Comp. Strength (N/mm^2)	Elastic Modulus (kN/mm^2)	Shrinkage (100 days) μstrain	Creep (70 days) μstrain	Max. Aggregate size (mm)	Admixtures
Gunthorpe	G1	Spray	60	31.1	751	421	5	Polymer modified
	G2	Spray	44	17.6	1311	809	Grade M	Acrylic copolymer
	G3	Spray	46	23.8	717	938	Conventional	Mortar mix
	G4	Hand	50	24	401	745	10	Styrene acrylic
	G5	Hand	50	19.6	1087	1411		Styrene acrylic
	G6	Hand	30	11.5	1100	1188		Styrene acrylic
	Substrate Concrete		36.2	28.1				
Lawns Lane								
	L1	Spray	60	22.7	620	783	3	Admixtures
	L2	Spray	60-65	30.3	325			Polymer modified
	L3	Spray	35	27.4	710	748		Shrinkage compensating
	L4	Spray	73	29.1	782	510	5	Admixtures
	L5	Spray		29.1	680	534	5	Admixtures
	Substrate Concrete		34.1	23.8				
Sutherland Street								
	S1	Flowing	65	24.2	740	445	5	Shrinkage compensating
	S2	Flowing	60	32.2	791	438		Shrinkage compensating
	S3	Flowing	70	31.9	580	667	6	Styrene acrylic
	S4	Flowing	45-50	27.4	388	454	Conventional	Concrete
	Substrate Concrete			23.2				