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Influence of elastic modulus on stress redistribution and cracking in repair patches

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Abstract

The paper presents the results of a field investigation of repairs to two highway bridges. The repairs were applied by spraying onto unpropped compression members of the bridges. Two categories of commercial repair materials were used, low stiffness materials relative to the substrate ($E_{rm} < E_{sub}$) and high stiffness materials relative to the substrate ($E_{rm} > E_{sub}$). The repair materials also represented a range of other properties such as strength, density, shrinkage, and creep. The results show that repairs applied with relatively stiff materials, $E_{rm} > E_{sub}$, display efficient structural interaction with the structure. High stiffness repairs are effective in redistributing shrinkage strain to the substrate and attracting external loading in the long term. Low stiffness repair materials ($E_{rm} < E_{sub}$) are much more likely to undergo tensile cracking due to restrained shrinkage. Low stiffness repairs are ineffective in redistributing strain.

Keywords: Creep; Elastic modulus; Long-term performance; Shrinkage; Structural interaction

1. Introduction

Repair and rehabilitation of reinforced concrete structures is a common requirement in modern construction. Steel reinforcement corrosion is a major cause of deterioration which disrupts the cover zone of reinforced concrete. Many types of repair materials are available commercially and the selection for reinstating a deteriorated concrete structure is usually done on a relatively ad hoc basis. Repair and rehabilitation of a reinforced concrete structure can only be successful if the new material interacts effectively with the parent concrete and forms a durable barrier against ingress of carbon dioxide and chlorides. Problems may arise since a dimensionally unstable repair material is placed against an aged (and, therefore, dimensionally stable) substrate concrete. Internal stress will be generated due to shrinkage and creep in the repair material which needs to be evaluated before a durable repair can be specified [1–3]. The stiffness (elastic modulus) of a repair material is important since it governs its load-sharing capacity [4,5].

Most standards and recommendations for repair material specifications [6–9] are based on limited quantitative knowledge of the structural interaction between the substrate concrete and repair patch during the service life of a structure. They do not take into account, in any significant quantitative manner, the mismatch in basic properties such as elastic modulus, shrinkage and creep on the long-term in-service performance of repair. Emphasis for repair material selection is usually placed on short-term properties such as strength (compressive, tensile, bond) and early age shrinkage. A critical evaluation of the recommendations of repair standards and material specifications [10,11] reveals significant limitations and contradictions.

Compatibility between repair material and substrate concrete is recognised to be important for prevention of cracking but reliable quantification of the required parameters is lacking. For example it has been recommended that the elastic modulus of a selected repair material should be within 10 N/mm^2 of the substrate concrete [5], but the research reported in this paper and elsewhere [12,13] provides overwhelming evidence that efficient repairs are achieved with repair patches of elastic modulus, E_{rm}, significantly greater than that of the substrate, E_{sub}.

Cracking may occur in repair patches due to shrinkage restraint provided by the substrate concrete and steel reinforcement. The effect of the mechanical interaction between different phases of a repair patch (repair material, substrate, reinforcement) on shrinkage cracking is not understood. Furthermore, there are no guidelines available for assessing the externally applied load- sharing capabilities of a repair patch during the service life of a structure.

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Fig. 1. Elevation of Gunthorpe bridge.

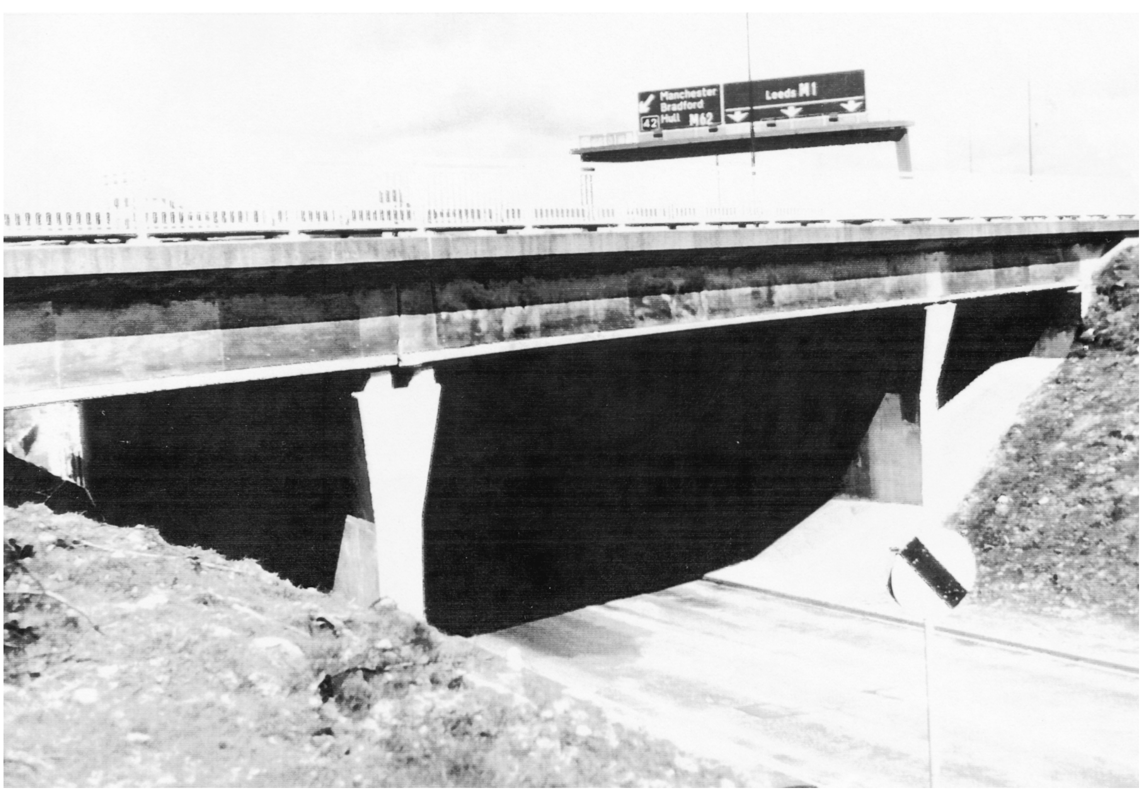

Fig. 2. Elevation of Lawns Lane bridge.

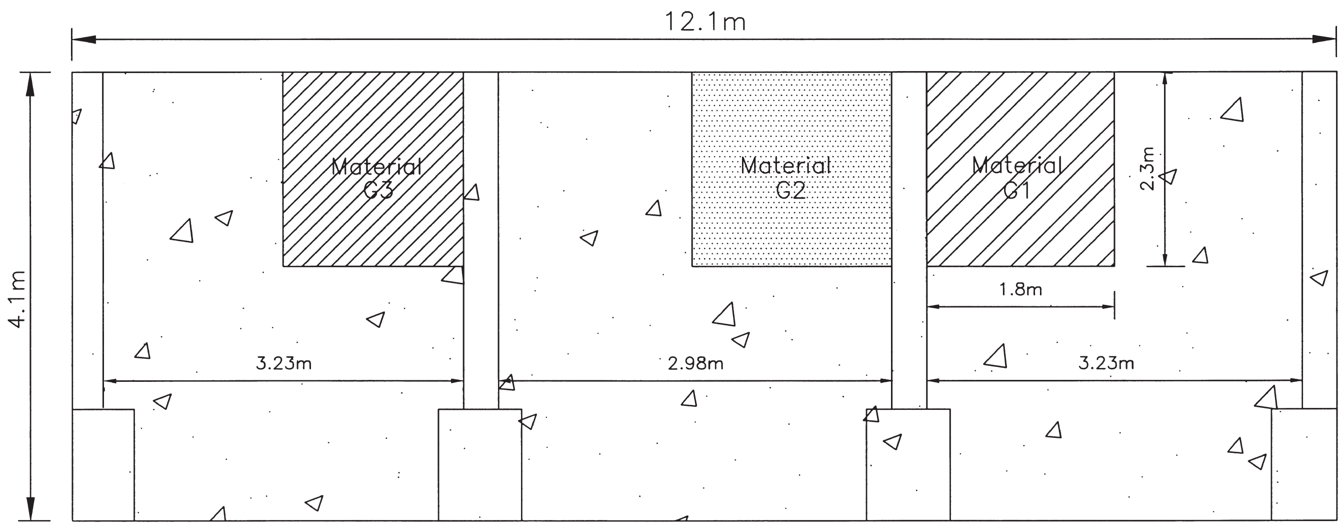

Fig. 3. Location of repair patches at Gunthorpe bridge.

The paper presents some of the results of a very wide ranging research project carried out to determine the factors which govern the interactions between repair and substrate materials and their influence on cracking and long-term load sharing. Both laboratory and field investigations were conducted. Structural elements of three reinforced concrete bridges were repaired and instrumented for long-term monitoring. Mainly commercially manufactured repair materials were used representing a typical range of elastic modulus, shrinkage and creep properties. Two categories of elastic modulus, $E_{rm} < E_{sub}$ and $E_{rm} > E_{sub}$ were considered. Repairs to the bridge elements were applied both in the propped and unpropped states adopting hand applied, sprayed and flowing repair methods. Field monitoring has been continuing for up to 240 weeks, along with some parallel laboratory investigations. The thermal and moisture fluctuations in the field were also recorded regularly. The thermal mass of the structural elements was too large for the internally monitored strains to be affected by local fluctuations of temperature and humidity. This paper is focused sharply on sprayed repairs applied with materials representing a typical range of shrinkage and creep properties but which clearly fall within the two categories of $E_{rm} < E_{sub}$ and $E_{rm} > E_{sub}$.

2. Experimental

2.1. Details of repair patches

Two deteriorating highway bridges of different forms of construction have been repaired and instrumented by means of vibrating wire strain gauges to monitor their long-term performance. The bridges were Lawns Lane bridge near Wakefield carrying part of the M1 South of Junction 42 and Gunthorpe bridge carrying the A6097 in Nottinghamshire, UK. Gunthorpe bridge is a reinforced concrete arch bridge spanning the River Trent in Nottinghamshire. It was built in 1927 and is comprised of a central arch and two side arches. Reinforced concrete beams support the deck laterally between the arches. An elevation of the bridge is shown in Fig. 1. Lawns Lane bridge is a three span reinforced concrete bridge which was built in the mid-1960s. It comprises insitu deck panels which are supported by prestressed concrete beams. The load is transferred to the foundations through piers and abutments. An elevation of the bridge is shown in Fig. 2.

The compression members of the bridges (piers and abutments) were repaired by spraying (gunite) repair patches as shown in Figs. 3 (Gunthorpe bridge) and Fig. 4 (Lawns Lane bridge). Prior to the application of repair, the deteriorated concrete was removed from the patches to a depth of 25 mm below the reinforcement level. The exposed reinforcement bars were cleaned and coated with a corrosion inhibitor. The bridge structures were maintained in an unpropped state throughout. Three repair materials were applied by spraying to the south abutments of Gunthorpe bridge (Fig. 3). One material (G1) had an elastic modulus, E_{rm}, greater than that of the substrate, E_{sub}. The remaining repair materials G2 and G3 had $E_{rm} < E_{sub}$. Lawns Lane bridge was repaired by spraying four different materials L1, L2, L3, and L4. Materials L2, L3, and L4 had $E_{rm} > E_{sub}$ while material L1 had $E_{rm} < E_{sub}$.

2.2. Gauge location and strain monitoring

The redistribution of strain with time in the different phases of a repair patch (substrate, reinforcement, repair material) was measured using vibrating wire gauges of gauge length 140 mm. The elevation and section through a typical repair patch is shown in Fig 5, with the location of vibrating wire gauges. One gauge is fixed on the cut-back interface of the substrate (labelled "subs"), one is welded on the steel reinforcement (labelled "steel"), and one is embedded within the repair material in the plane of reinforcement and equidistant from adjacent reinforcing bars (labelled "emb"). The strain gauges were connected to a data logger

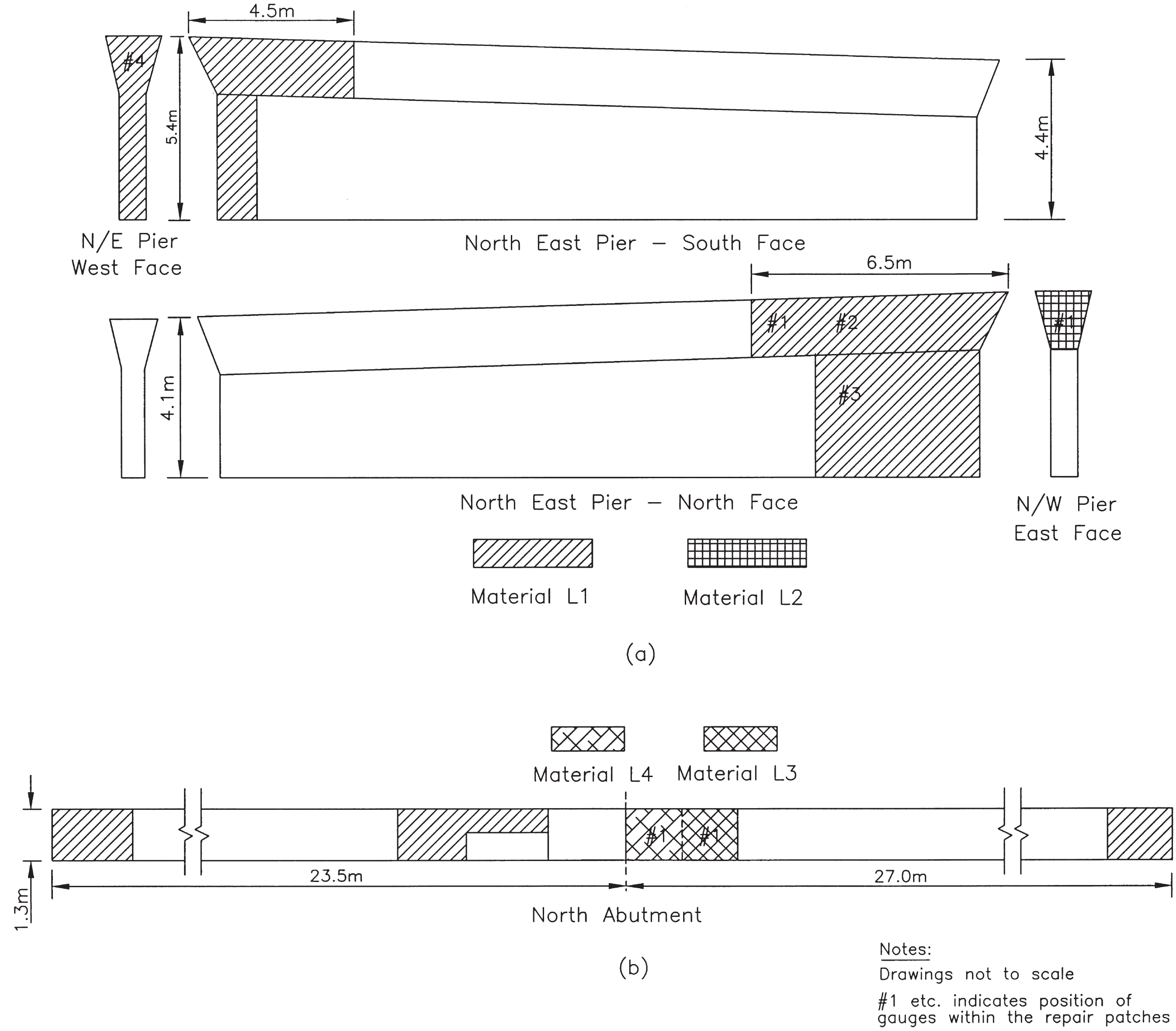

Fig. 4. Location of repair patches at Lawns Lane bridge.

which automatically recorded the strain readings at regular intervals up to a monitoring period of 60 weeks.

2.3. Repair materials

The primary properties of repair materials whose influence on the long-term composite action between a repair patch and the substrate concrete considered are elastic modulus, shrinkage, and creep. These properties were determined in the laboratory using prism specimens of dimensions 100 $\times$ 100 $\times$ 500 mm. The elastic modulus was determined at 28 days age according to BS1881, Part 121 (1983). The test procedures for the free shrinkage and creep properties are outlined in a previous paper [11]. In order to determine the relative properties of each repair material and the substrate concrete, 100-mm diameter, 150-mm long core samples were obtained from the substrate of the two highway bridges. The elastic modulus and compressive strength of the substrate concrete cores was determined in accordance with BS1881 Part 121 and 120 (1983) respectively.

The properties of the repair materials and substrate concrete are given in Table 1. It is important to note that repair materials G2, G3, and L1 were less stiff than the substrate ($E_{rm} < E_{sub}$) and the remaining repair materials were stiffer than the substrate ($E_{rm} > E_{sub}$). The repair materials were commercial products (except G3) suitable for the dry spray (gunite) process. Their details are as follows:

Material G1 incorporates a rapid hardening Portland cement (≥400 kg/m^3), 5 mm (maximum) size graded aggregate, microsilica and a co-polymer.

Material G2 is a blend of rapid hardening Portland cement, microsilica, fibres and spray dried styrene acrylic copol-

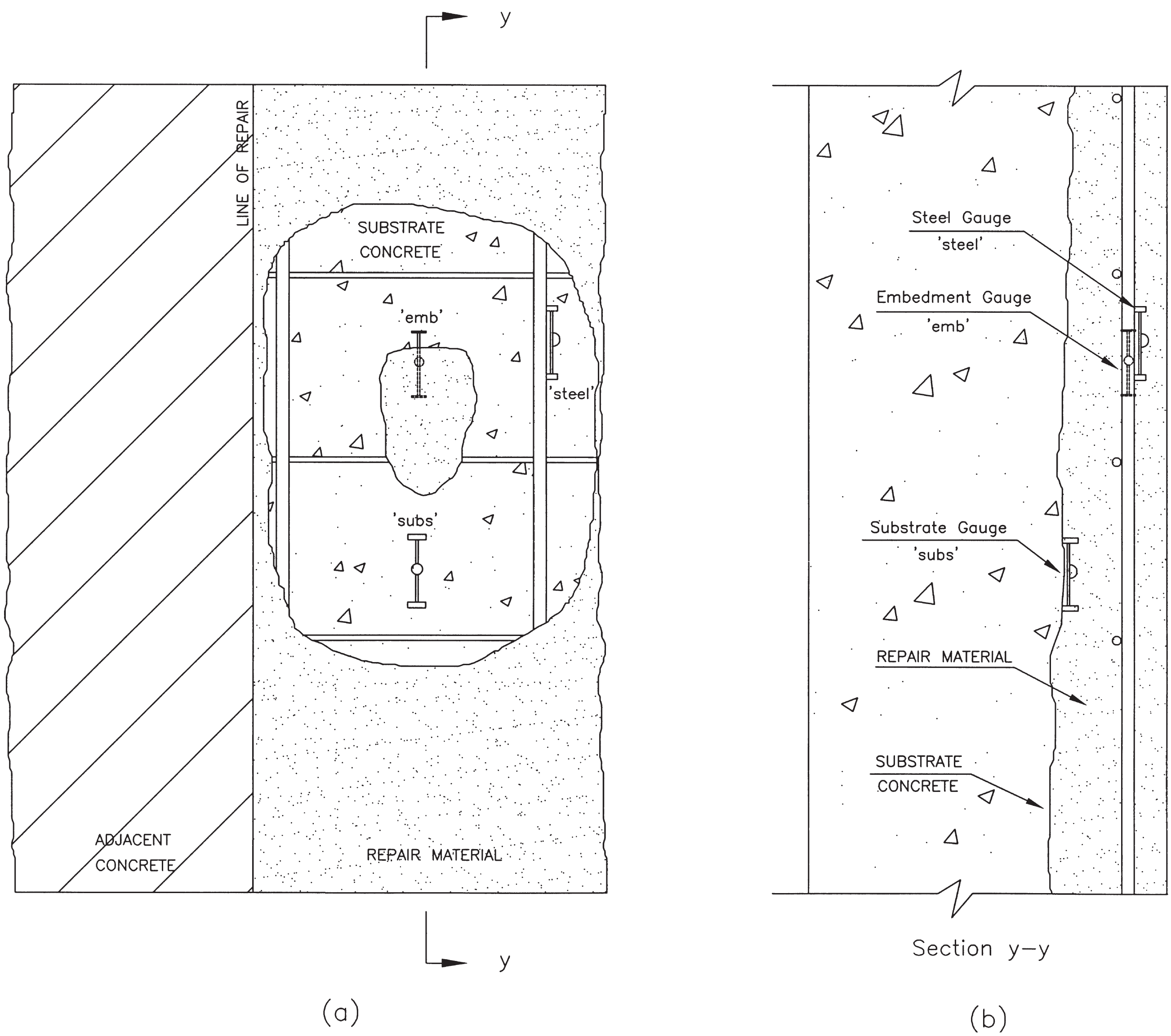

Fig. 5. Location of vibrating wire strain gauges within a repair patch (a)elevation, (b)section through repair patch.

Table 1
Properties of materials

Material	Compressive strength (N/mm^2)	Modulus of rupture (N/mm^2)	Elastic modulus (kN/mm^2)	Density (kg/m^3)	Free shrinkage[a] (microstrain)	Creep[b] (microstrain)	$\frac{E_{rm}}{E_{sub}}$	Bridge
Substrate	42		28.1		-	-	-	
G1	60	2.2	31.1	2250	751	421	1.10	Gunthorpe Bridge
G2	57	3.7	17.6	2250	1311	809	0.63	
G3	46	3.4	23.8	2200	717	938	0.85	
Substrate	45		23.8		-	-	-	
L1	60	6.1	22.7	2210	620	783	0.95	Lawns Lane Bridge
L2	60	7.0	30.3	2100	325	not available	1.27	
L3	35	1.9	27.4	1850	710	748	1.15	
L4	60	4.7	29.1	2270	782	510	1.22	

[a] Free shrinkage strain at 100 days, stored at 20°C, 55% RH.
[b] Compression creep, stress/strength 30%, 70 days under load.

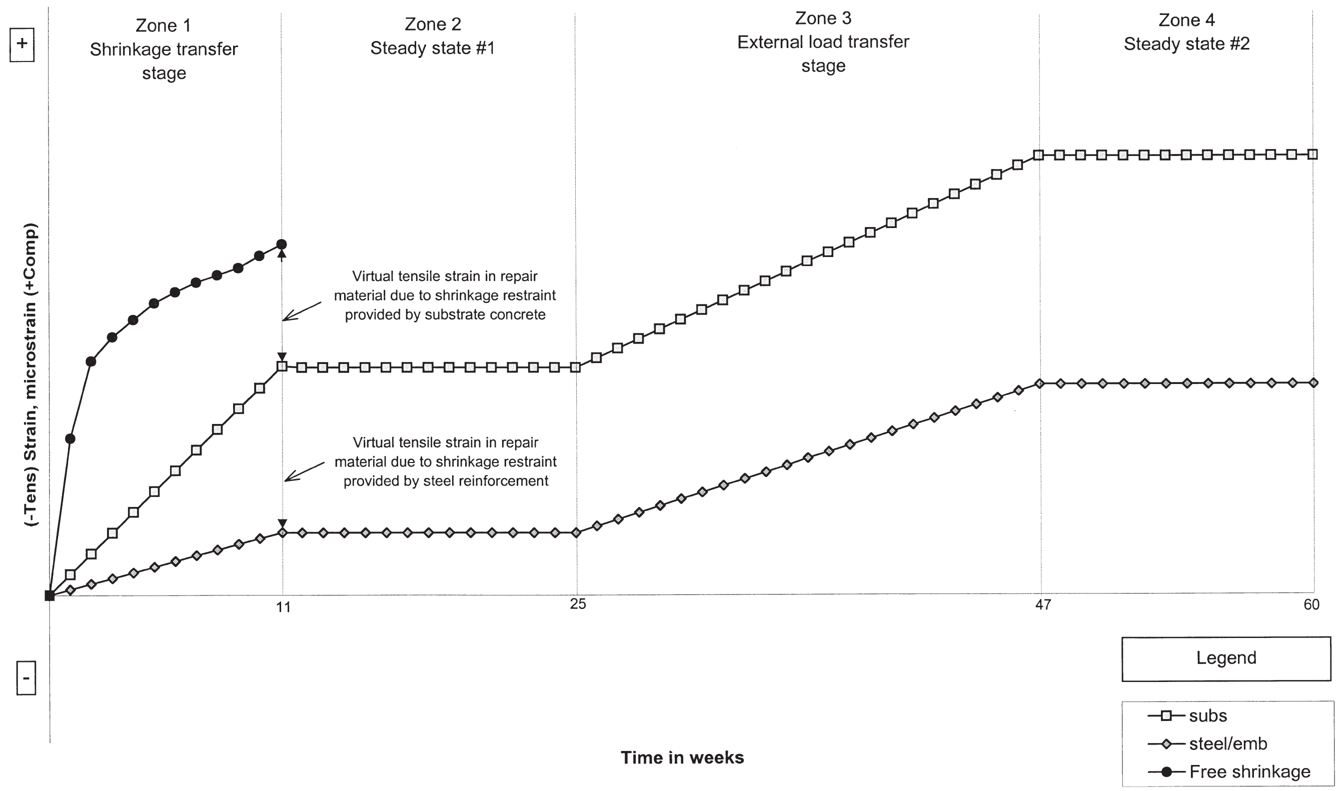

Fig. 6. Schematic representation of strain redistribution with time within a repair patch. $E_{rm} > E_{sub}$ [12].

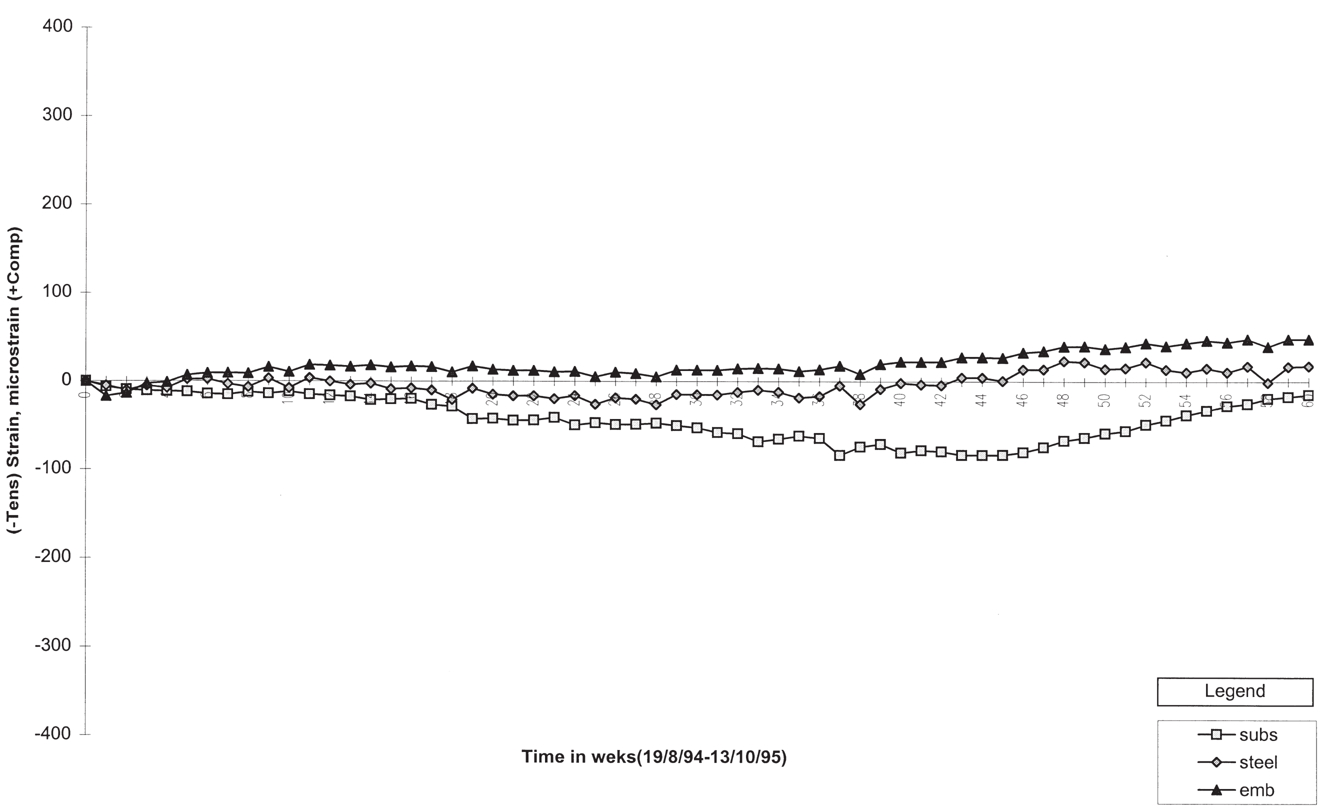

Fig. 7. Strain-time relationships for the repair patch of material G2 at Gunthorpe bridge.

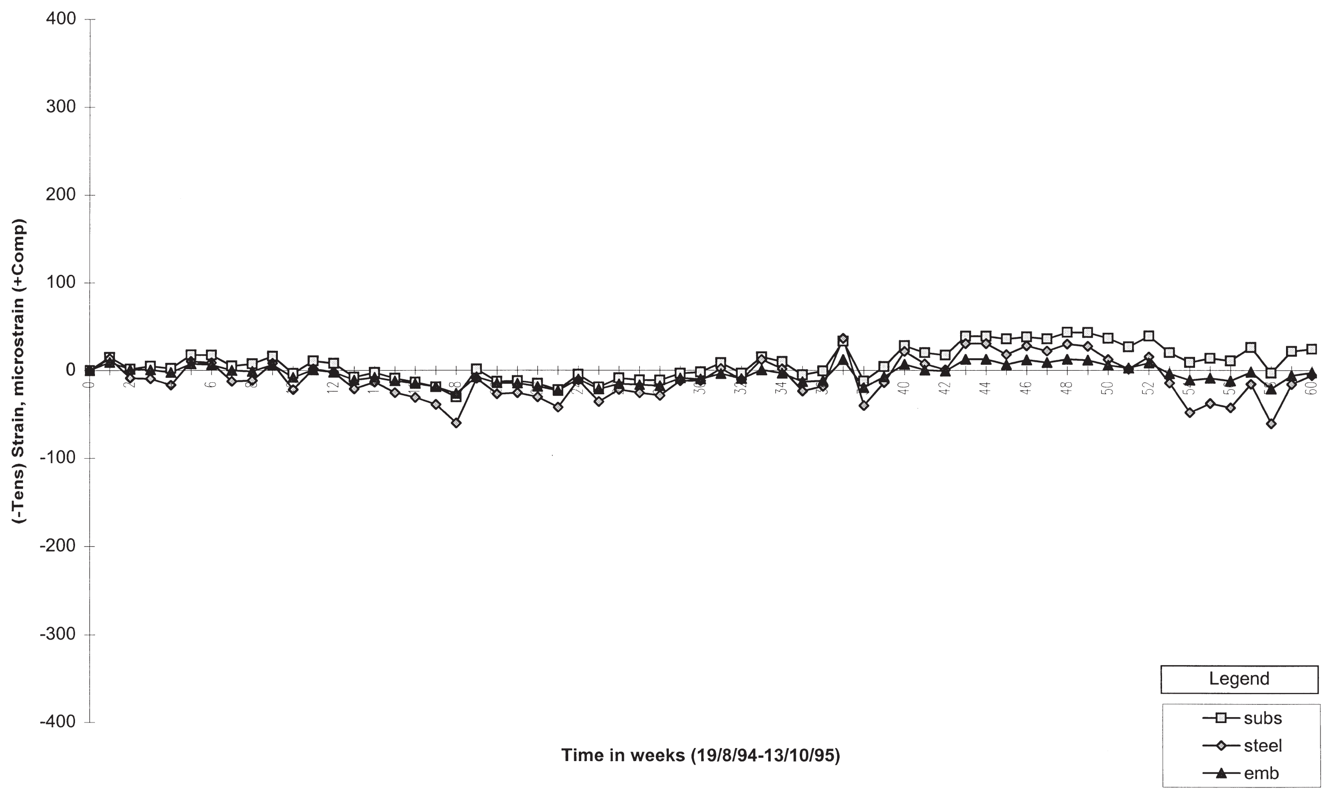

Fig. 8. Strain-time relationships for the repair patch of material G3 at Gunthorpe bridge.

ymer. The blended material to sand ratio for guniting is 1:4 with water/cement of 0.35 to 0.40.

Material G3 is a laboratory designed mix comprising ordinary Portland cement, medium grade sand. Its water/cement was controlled at the nozzle by an experienced operator for dry spraying. The mix was used for comparing the performance of a normal mortar mix with commercial repair materials.

Material L1 is a blend of low alkali Portland cements, microsilica, limestone aggregate and shrinkage reducing admixtures. The water/powder ratio is 0.12. This was the only material approved by the Resident Engineer at Lawns Lane bridge since it fully complied with the repair specification BD 27/86 [6] of the Highways Agency.

Material L2 is a polymer modified repair mortar.

Material L3 is based on Portland cement, graded aggregates, special fillers and chemical additives. Typical water/cement is 0.18.

Material L4 contains Portland cement, silica sand, admixtures, plastic fibres. The maximum aggregate size is 5 mm. The water/cement is 0.35.

3. Results and discussion

3.1. Strain-time relationship, $E_{rm} > E_{sub}$

A detailed presentation of the strain-time relationships of the different phases of a repair patch incorporating repair materials with $E_{rm} > E_{sub}$ is made in another publication [12]. This applies to materials G1 (Gunthorpe bridge) and L2, L3, and L4 (Lawns Lane bridge). All repair materials with $E_{rm} > E_{sub}$ resulted in a typical strain-time profile for the substrate (gauge "sub"), the steel reinforcement (gauge "steel") and the repair material (gauge "emb"). A schematic representation is given in Fig. 6 based on the field data monitored over a period of 60 weeks [12]. Fig. 6 shows four distinct stages of strain (and, therefore, stress) redistribution with time.

Zone 1 is the shrinkage transfer stage which occurs between time 0 (24 hours after application of repair) and 11 weeks. During this stage, the stiffer repair material ($E_{rm} > E_{sub}$) gradually transfers some of its steadily increasing shrinkage strain to the substrate concrete at the interface. As a result, the shrinkage restraint provided by the substrate to the repair material is reduced, thereby reducing the resulting tension in the repair material. The strain in the steel reinforcement (gauge "steel") and the repair material at the level of steel reinforcement (gauge "emb") also increases linearly with time in Zone 1. The strain, however, is much lower than the free shrinkage of the repair material (also plotted in Fig. 6) due to the restraint provided both by the steel reinforcement and the substrate concrete. Fig. 6 also shows that at week 11, the tension in the repair material caused by shrinkage restraint provided by the reinforcement is much greater than that caused by the shrinkage restraint provided by the substrate. This is due to the greater stiffness of steel ($E_s >> E_{rm}$ whereas E_{rm} is marginally greater than E_{sub}).

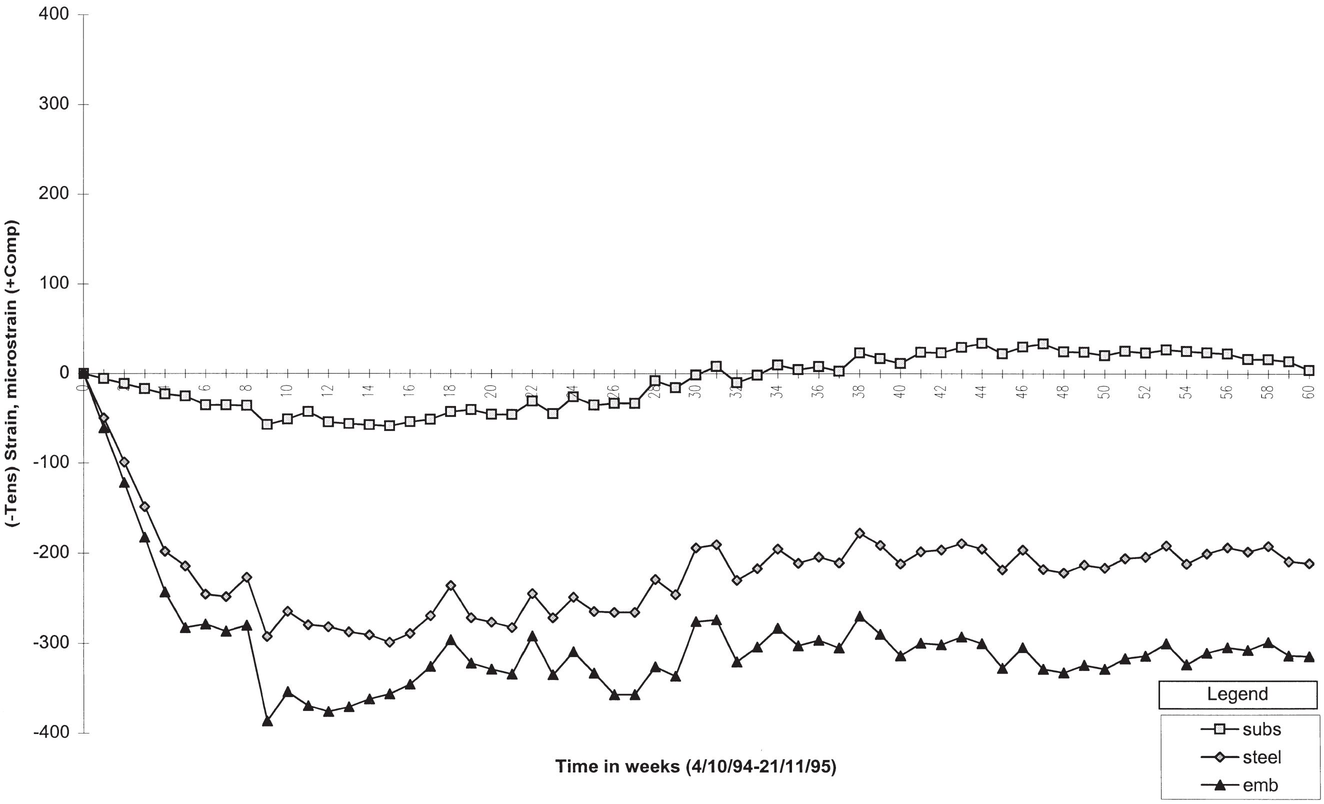

Fig. 9. Strain-time relationships for the repair patch of material L1 at Lawns Lane bridge.

Zone 2 which extends from week 11 to 25 is termed as steady state #1. During this period the increase in the free shrinkage of the repair materials becomes negligible [2,11] Therefore, there is no transfer of shrinkage strain to the substrate.

Zone 3 is the external load transfer stage when the externally applied load to the substrate of the compression member gradually starts redistributing to the repair patch of $E_{rm} > E_{sub}$. This zone extends between weeks 25 to 47.

After week 47, the repair patch reaches the final steady state (Zone 4) when no further redistribution of strain (or stress) takes place.

3.2. Strain-time relationship, $E_{rm} < E_{sub}$

The development of strain with time in the three phases of repair patches (substrate, steel, repair material) which incorporated different repair materials with $E_{rm} < E_{sub}$ is presented in Figs. 7, 8, and 9. The three repair materials are G2 with $E_{rm} = 0.63\ E_{sub}$ (Table 1), G3 ($E_{rm} = 0.85\ E_{sub}$), and L1 with $E_{rm} = 0.95\ E_{sub}$. A comparison between the strain-time profiles of repair patches with $E_{rm} > E_{sub}$ (Fig. 6) and the profiles in Figs. 7, 8, and 9 for patches with $E_{rm} < E_{sub}$ shows radical differences between the two sets. Figs. 7, 8, and 9 show none of the strain (and, therefore, stress) transfer stages which are clearly identified in Fig. 6 (Zone 1, 2, 3 and 4).

3.2.1. Shrinkage transfer stage (Zone 1)

Figs. 7, 8, and 9 show that repair materials with $E_{rm} < E_{sub}$ are unable to transfer any shrinkage strain into the stiffer substrate during the previously defined shrinkage transfer period (weeks 0 to 11). No (or insignificant) compressive strains due to repair material shrinkage are transferred either to the substrate concrete or the steel reinforcement during this period. Negligible strains are observed within the repair materials G2 and G3 (gauge "emb", Figs. 7 and 8) despite the high free shrinkage of these materials, (1311 and 717 microstrain respectively, Table 1). This is due to the stiffer substrate (and steel reinforcement) effectively restraining the shrinkage of the repair materials. This firm restraint to shrinkage induces a higher tensile stress in the repair material if $E_{rm} < E_{sub}$ compared with a repair patch where $E_{rm} > E_{sub}$ (Figs. 6–9). If the tensile stress exceeds the tensile capacity of the repair material, cracking will occur.

3.2.2. Restrained shrinkage cracking

Restrained shrinkage cracking was absent during the monitoring period in all materials with $E_{rm} > E_{sub}$ (i.e., materials G1, L2, L3, and L4). The surfaces of these repair patches were finished with a steel float. The low modulus material L1 ($E_{rm} < E_{sub}$) which was also finished with a steel float, showed extensive tensile cracking within 5 weeks of application. Fig. 9 shows that tensile strain in the

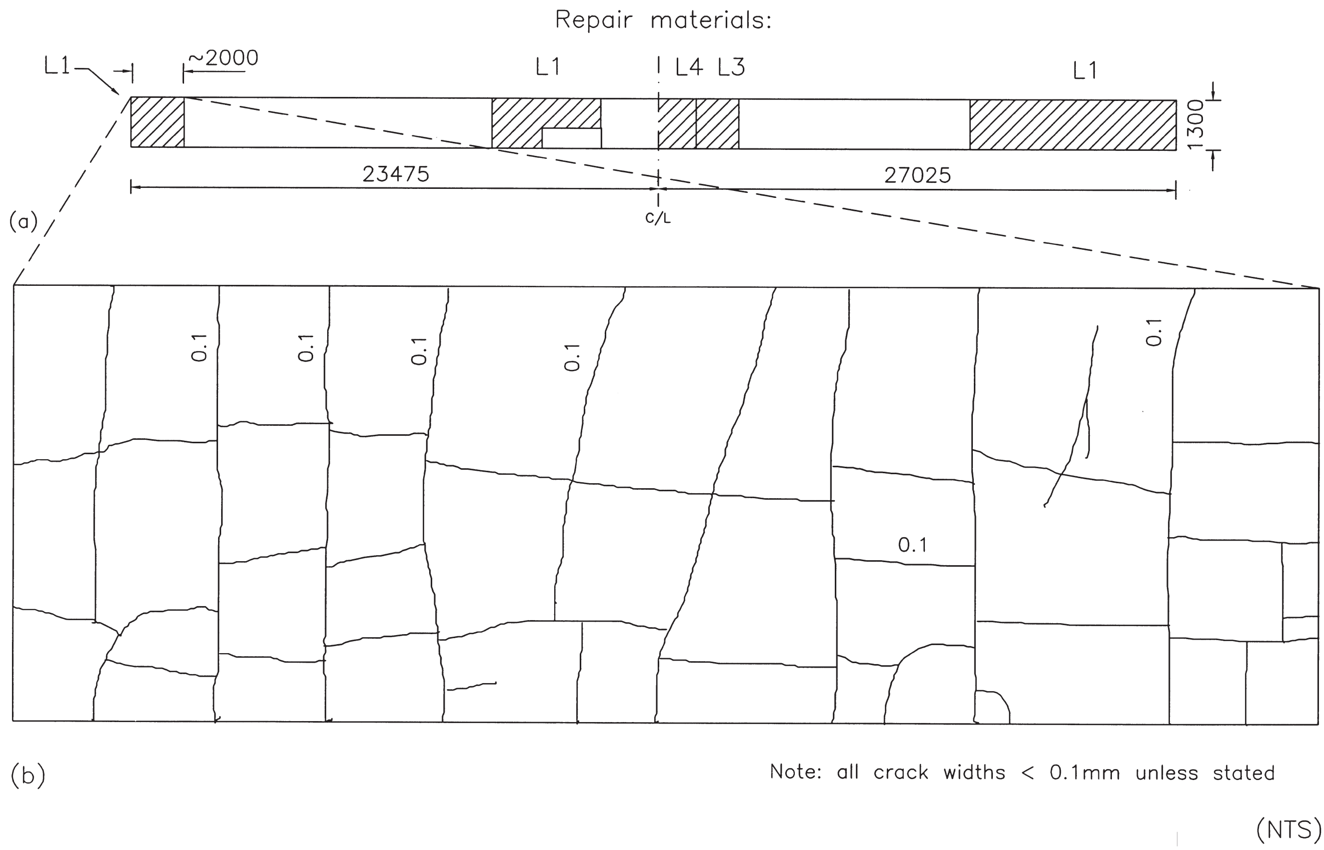

Fig. 10. Typical crack pattern in repair material L1 ($E_{rm} < E_{sub}$) due to restrained shrinkage.

"emb" gauge increases sharply to exceed values of 250 microstrain which resulted in cracking. The crack widths are included in the strain values. Typical crack patterns developed by the repair patches of material L1 are shown in Fig. 10. Ironically, L1 was the only repair material approved by the resident engineer (according to BD27/86 [6]) at Lawns Lane. No surface cracking could be observed in the low modulus repair material G2 for two possible reasons. First, surface of the repair was left in a rough unfinished state (no floating) which made crack observation difficult. Secondly, the material was reinforced with fibres which restrict cracking. The low modulus material G3 was finished with a wooden float. Shrinkage cracking appeared in this material at some locations, developing crack widths of up to 0.7 mm.

3.2.3. External load transfer stage

During the external load transfer stage, weeks 25 to 47 (Fig. 6), the low modulus repair patches ($E_{rm} < E_{sub}$) show insignificant change in tensile strain distribution (Figs. 7–9). The strains remain negligible during weeks 25 to 47 in Figs. 7–9 except when the repair patch undergoes restrained shrinkage cracking (Fig. 9). This implies that the lower stiffness repair materials are unable to attract external applied load from the substrate during the load transfer stage.

3.3. Repair–substrate interaction

A compression member repaired in an unpropped state is considered in Fig. 11. A section through the compression member before and after the removal of the deteriorated concrete is shown in Figs. 11a and 11b respectively. The stage after the application of the repair patch (0 to 11 weeks) is represented by Figs. 11c, 11d: Case 1 ($E_{rm} < E_{sub}$) and by Figs. 11c, 11d: Case 2 ($E_{rm} > E_{sub}$).

Fig. 11c, case 1: shows the idealised free shrinkage strain in the repair (exaggerated). During the shrinkage transfer period (weeks 0 to 11), the stiffer substrate concrete effectively restrains the repair material from shrinking. As a result, the free shrinkage of the repair material is fully restrained, translating it into tensile stress as shown in Fig. 11d (case 1).

Fig. 11c, case 2: $E_{rm} > E_{sub}$ shows that during the shrinkage transfer period (weeks 0 to 11), the stiffer repair material transfers some of its shrinkage strain to the substrate at the interface. Consequently, the restrained shrinkage strain at the interface, which results in tension in the repair material, is equivalent to the difference between the free shrinkage of the repair material and the shrinkage strain transferred to the substrate (Fig. 11d, case 2). For repair materials with similar shrinkage characteristics, therefore, the case of $E_{rm} > E_{sub}$ will result in much lower restrained shrinkage tension compared with the case of $E_{rm} < E_{sub}$ (compare Figs. 11d, case 1 and case 2). The consequently greater risk of cracking in repair patches with $E_{rm} < E_{sub}$ is obvious. The strain gradients set up in the repair patch and in the substrate (Fig. 11d, case 2) are due to the reduction in shrinkage restraint with increasing distance from the interface.

Fig. 11e (case 1: $E_{rm} < E_{sub}$) and Fig. 10 show that the relatively high tension produced by restrained shrinkage causes the classical horizontal (and vertical) cracking, at regular spacing, in the repair patch.

The alternate cases of longer-term relaxation of tensile stress due to creep in Fig. 11f (case 1: $E_{rm} < E_{sub}$, case 2: $E_{rm} > E_{sub}$) occur if the inter-relationships between relative stiff-

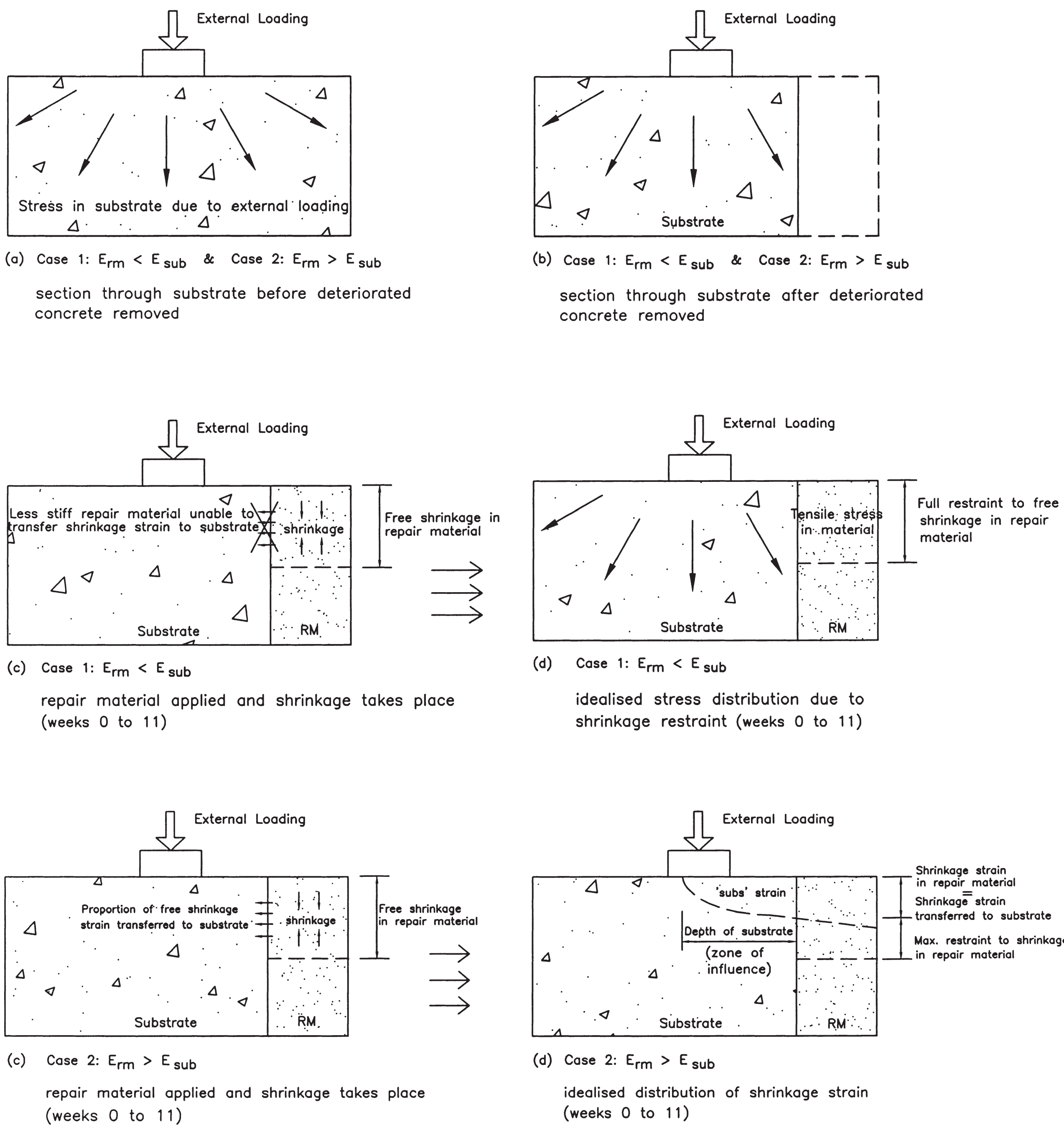

Fig. 11. Long-term interaction between repair and substrate. Case 1: $E_{rm} < E_{sub}$, Case 2: $E_{rm} > E_{sub}$.

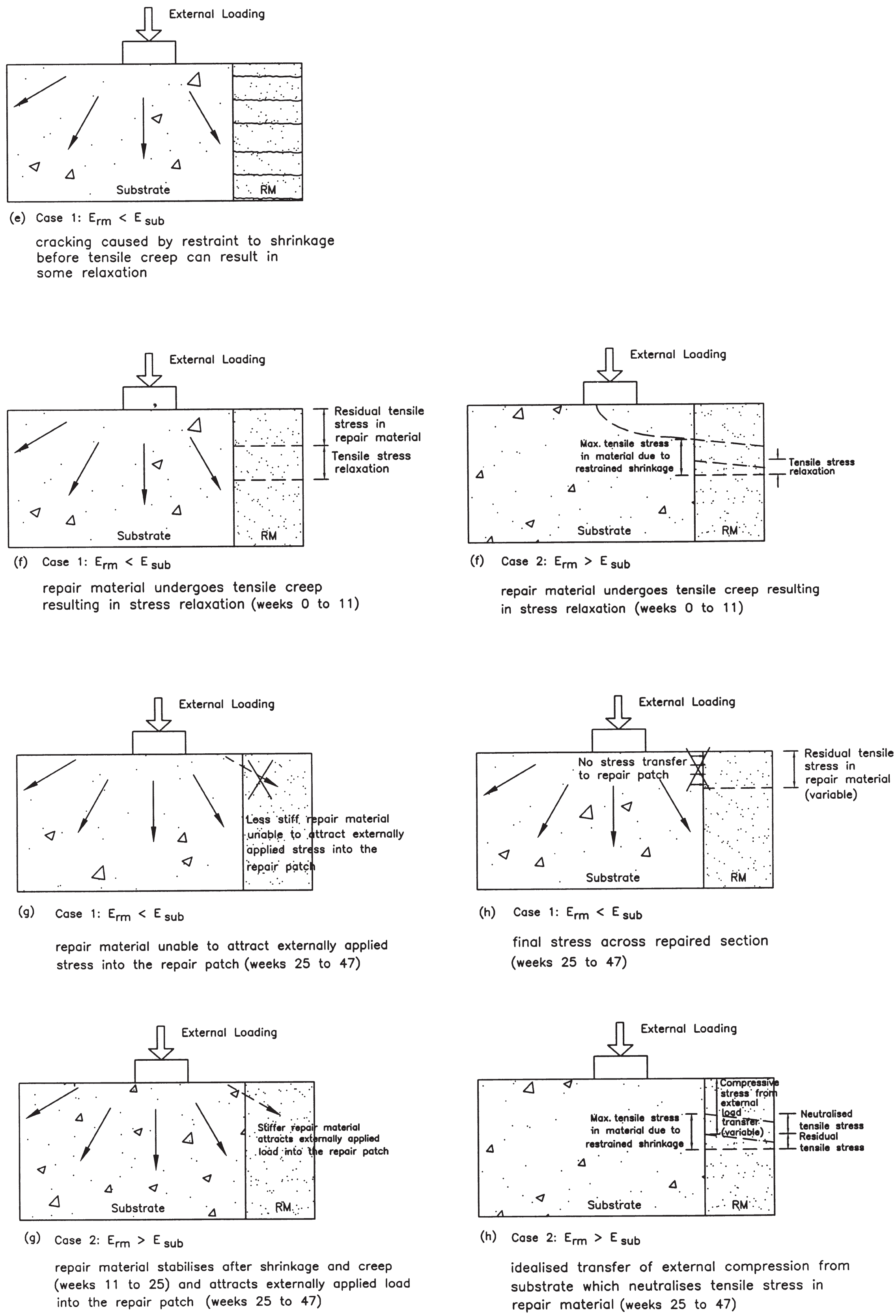

Fig. 11. (*Continued*).

ness E_{rm}/E_{sub}, free shrinkage and creep of the repair material are such that maximum tensile stress never exceeds the tensile strength. This is more likely to occur when $E_{rm} > E_{sub}$.

Figs. 11g and 11h (case 1) and Figs. 11g and 11h (case 2) represent the long-term interaction between the repair patch and the substrate with respect to externally applied load transfer (weeks 25 to 47). In case 1: $E_{rm} < E_{sub}$, (Fig. 11g: case 1) no transfer of external load to the repair patch takes place and consequently the final stress in the repair is as represented in Fig. 11h (case 1). In case 2: $E_{rm} > E_{sub}$ (Fig. 11g), effective load transfer into the repair patch takes place. The result can either be a reduced tensile stress or net compression in the repair patch, Fig. 11h: case 2).

3.4. Limitations of repair material specifications

Repair materials G1, G2, and G3 (used at Gunthorpe bridge) and L1, L2, L4 (used at Lawns Lane bridge) have much greater compressive strength than their respective substrate concretes (Table 1). On this basis, they satisfy a key criteria of standard specifications of repair [7–10]. Repair material L3, on the other hand, has a much lower compressive strength than the substrate and its modulus of rupture is also very low (Table 1). According to current practice [7–10] it would not be approved for reinforced concrete repair. The results presented in this paper, however, show that material L3 performed satisfactorily whereas materials G3 and L1 failed. The high stiffness ($E_{rm} > E_{sub}$) of material L3 is responsible for its satisfactory performance. Compressive strength of repair materials is of secondary importance. The maximum compressive stresses transferred to a repair patch during external load transfer are very small ($<$5 N/mm^2) [12]. Current repair standards do not quantify the critical interrelationships between stiffness, shrinkage and creep required of repair materials.

4. Conclusions

The following conclusions are based on field monitoring of spray applied repairs to unpropped compression members of highway bridges.

1. Repairs applied with relatively stiff materials, $E_{rm} > E_{sub}$, display efficient interaction between the repair patch and the substrate structure. They undergo effective (i) strain (and, therefore, stress) transfer to the substrate during the shrinkage period of the repair material, thereby reducing restrained shrinkage tension and (ii) strain transfer to the repair patch in the long-term due to external load transfer from the substrate structure.

   Repairs applied with low stiffness materials, $E_{rm} < E_{sub}$, display no structural interaction. The strain transfer stages between the phases (substrate, repair, reinforcement) are absent both in the short and long term.
2. Low stiffness repair materials relative to the substrate, ($E_{rm} < E_{sub}$), are more likely to undergo tensile cracking due to restrained shrinkage than high stiffness repairs, $E_{rm} > E_{sub}$.
3. The relative stiffness of repair and substrate materials, E_{rm}/E_{sub}, is the primary parameter for the design of efficient repairs, other parameters such as strength are relatively unimportant. The requirement is that E_{rm} should be greater than E_{sub}.
4. Current standards of repair specifications have significant limitations for the design of efficient repairs.

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