MATERIALS FOR THE REPAIR AND STRENGTHENING OF CONCRETE STRUCTURES: THE INFLUENCE OF MATERIAL PROPERTIES ON STRUCTURAL PERFORMANCE

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ABSTRACT

This paper reviews a number of research programmes which have been undertaken in collaboration with industry concerning the selection of materials for the repair and strengthening of concrete structures. The research has been primarily concerned with those material properties which affect the structural performance and durability of patch repaired systems and the selection of appropriate adhesives for strengthening using the technique of bonded external reinforcement. The important material characteristics for patch repair systems are identified and, using appropriate test procedures, the properties of a range of generically different materials are presented. Similarly, the properties of adhesives which are relevant to satisfactory structural performance in plate bonding schemes are discussed and the influence of temperature and moisture on these systems is emphasized. Finally, the paper presents the outcome of both analytical and experimental studies concerning the structural integrity of patch repaired column and beam elements, including the effect of repairing the structure whilst still under load.

KEYWORDS

Repair, materials, strengthening, adhesives, concrete

A mismatch in coefficient of thermal expansion or subsequent shrinkage of the repair material may result in differential strains between the repair material and the concrete substrate which eventually lead to interfacial bond failure. A material which exhibits high creep may become less effective structurally with time under sustained load. The significance of a mismatch in modulus of elasticity will be explained later in this paper by reference to the predicted and observed behaviour of repaired elements.

DURABILITY OF PATCH REPAIR SYSTEMS

Further material characteristics of importance in ensuring satisfactory durability of repair materials will include:

(a) the effect of curing temperature and temperature in-service on adhesion to the substrate concrete
(b) the effect of thermal, moisture and freeze-thaw cycling on adhesion strength
(c) the effect of cyclic loading in-service on adhesion strength
(d) the effect of temperature on modulus of elasticity, tensile strength and development of compressive strength
(e) permeability to water, gases and salt solution

These matters have been investigated by Chandler and Mays (1998) in connection with the repair of concrete pavements, again using a range of generically different repair systems. Temperatures in (a) and (d) ranged from $5^{\circ}C$ to $30^{\circ}C$ whilst the thermal and moisture cycling in (b) involved temperatures up to $40^{\circ}C$ and "thunder-shower" conditions.

For each property, the repair materials were ranked in order of performance and points awarded on a scale of 1 to 10. The results are summarised in Table 2. The polyester resin, high alumina cement and opc/sand materials performed poorly, particularly with respect to adhesion to the substrate after thermal, moisture and load cycling. Overall, the remaining materials performed satisfactorily.

STRUCTURAL PROPERTIES OF ADHESIVES FOR BONDED EXTERNAL REINFORCEMENT

The purpose of the adhesive in bonded external reinforcement is to produce a continuous bond between the reinforcing plate and the concrete to ensure that full composite action is developed by the transfer of shear stress across the adhesive layer. A typical adhesive shear stress distribution in a plated beam as derived by Mays (1993) is shown in Figure 1(a), from which it can be seen that the shear stress increases to a value of about 4 times the mean value at the plate ends. This is because the external plate has to be curtailed in a tension zone and as a result normal, or peeling, stresses are also generated at the plate ends as shown in Figure 1(b).

The magnitude of these stress concentrations is heavily dependent on the modulus of elasticity of the adhesive, as shown in Figure 2. The modulus may vary from one adhesive to the next and as a result of temperature variations or plasticisation by water. In order to control the magnitude of stress concentrations a maximum value of 8 to 10 kN/mm^2 is normally recommended. However, at very low values of modulus (<0.1 kN/mm^2) stress transfer becomes affected significantly. Since long-term creep effects can be related to further decreases in elastic modulus, an initial adhesive elastic modulus of at least $2kN/mm^2$ would seem desirable.

Figure 3 shows typical creep relationships between "normalised" stress and time to failure for steel double overlap joints made with a cold-cure (5° – 30° C) epoxy. It is normally recommended that any sustained stress in the adhesive be kept below 25% of the short-term joint strength in order to minimise any creep effect. The significant reducti[on in] performance at higher temperatures will be referred to later.

If the joint is likely to be subjected to cyclic loads during service, a fatigue asses[sment] must be carried out. A typical relationship between the stress range applied to double [overla]p joints and the number of cycles to failure is shown in Figure 4. A limit is normally placed on the shear stress range in the adhesive in service (eg $4N/mm^2$). Again, the significant effect of elevated temperatures should be noted.

INFLUENCE OF TEMPERATURE AND MOISTURE ON STRUCTURAL ADHESIVES

Not only is the rate of cure of an adhesive sensitive to the ambient temperature and humidity but so also are its mechanical properties in the hardened state. Of particular significance is the temperature at which thermosetting adhesives such as epoxies change from a "glassy" to a "rubbery" phase. This Glass Transition Temperature, T_g, may be as low as 40°C for some "cold-cure" construction epoxies and it signifies the temperature at which there is a marked reduction in engineering properties.

The effect on creep and fatigue performance of temperatures in excess of T_g (ie testing at 55°C) is well illustrated in Figures 3 and 4. The effect of temperature on the flexural modulus of a range of epoxy adhesives is shown in Figure 5. For applications in hot climates, "warm-cure" (50 – 80°C) variants are available with T_g values increased to 70 – 80°C.

Many adhesives absorb moisture, in some cases the saturation level reaching 8% by weight. This has the effect of causing plasticisation and the effect on flexural modulus is shown in Figure 6. To limit this effect a maximum water uptake of 3% by weight is normally specified for structural adhesives. In addition, the long-term stability of the adhesive/substrate interface must be checked since this will be of vital importance to joint durability. For this purpose a durability test involving a self-stressed wedge joint is suggested.

STRUCTURAL BEHAVIOUR OF REPAIRED ELEMENTS

Three dimensional linear elastic finite element techniques have been used by Emberson and Mays (1990 and 1996) to develop an understanding of load transfer through simple patch repairs in reinforced concrete members subject to either axial (Figure 7) or flexural (Figure 8) loading. As might be expected, a low E value for the repair material generates relatively high stresses in the substrate concrete and the possibility of high longitudinal interfacial shear stresses.

Concentrations of stress also occur in the concrete immediately adjacent to the transverse interface with the repair material. In the tension zone this may lead to premature flexural cracking and may also have long-term durability implications.

Conversely, a high E value for the repair material causes load to be attracted into the repair, thus placing greater structural demands upon the material. In zones of tension stress this may result in a requirement for an extremely high bond stress at the transverse interface between the repair material and concrete, otherwise interfacial failures may occur.

Experimental programmes have also been conducted on reinforced concrete elements loaded in either axial tension or flexure. For the specimens loaded axially in tension, a total of nine generically different repair systems were used. The experimental strain results showed good agreement with the finite element predictions in the elastic range provided there were no interfacial adhesion failures. Such failures occurred with the polyester resin and the unmodified cementitious mortar.

For the flexural specimens six repair systems were used, four of which were common with the axially loaded prisms. Again, the tests confirmed the accuracy of the finite element predictions, particularly as far as mismatch in elastic modulus is concerned for repairs on the compression face. For repairs on the tension face, the tensile strength of the repair material appears to be a more important parameter, high values generally enhancing flexural performance.

Repaired flexural specimens were also subject to creep and fatigue trials. In the former, a sustained load of approximately one-third of ultimate was maintained for a period of at least one year. The results showed that when the patches extend into the shear spans, the mechanical properties of the materials start to have an effect on the creep performance. For example, a beam repaired with the acrylic resin mortar exhibited relatively high creep deflections, a result which reflects the value of creep strain measured in long-term creep tests on the pure material.

Load cycling of repaired beams was conducted at 1 Hz over a load range of approximately 30% of ultimate. In all cases failure occurred as a result of tensile fatigue fracture of the main reinforcement steel.

REPAIRS UNDER LOAD

The experimental work referred to above was based on 'ideal' specimens fabricated under laboratory conditions and repaired under zero load. Mays and Barnes (1995) extended this work to account for the load state of the structure during repair, the method of removing the concrete and the interaction of bending and axial loads in members. To this end, reinforced concrete H-frames were designed on a scale of 1:2.5 to represent either a typical internal ground-floor frame in a building or a bridge sub-structure. Figure 9 shows a schematic arrangement of a repaired H-frame within the loading rig.

A total of seven frames were constructed, one to act as a control and three with each of two repair materials. These were a spray-applied micro-concrete and a hand applied acrylic modified cementitious repair material. The repairs were applied by a specialist repair contractor to concrete surfaces which had been prepared using either grit blasting or water jetting. Three alternative load states were employed during the repair process:

- no load at repair (representing a propped structure);
- equivalent of dead load at repair;
- equivalent of combined dead and imposed load at repair.

A programme of loading and unloading cycles was conducted on each frame to simulate operation under design loads, before finally loading to failure. Strain and deflection readings were taken throughout. The load-deflection curves for frames repaired under zero load were similar to each other and to that of the unrepaired control frame as shown in Figure 10. Also, there was no significant difference in overall behaviour between the two frames repaired with different materials under a load simulating dead load only. At lower levels of load there was an understandable variation in load-deflection characteristics as compared with the frames repaired under zero load, because some deflection had occurred before repair. However, at loads exceeding 60% of ultimate, the effect of load level at the time of repair became insignificant. Similar deductions could be drawn for the two frames repaired under a load simulating dead and imposed load.

Examination of the strain readings revealed essentially linear strain distributions across the section, thus providing strong evidence that full composite action is occurring across the repaired section.

CONCLUSIONS

The results of the programmes of research summarised in this paper have led to the following conclusions with respect to the structural repair and strengthening of concrete:

(a) The desirable characteristics of repair systems for satisfactory structural performance have been identified. European Standards for the specification and testing of repair materials are becoming available for the measurement of the relevant mechanical and physical properties of the material. From the results of such tests it is possible to draw some conclusions as to the suitability of a system of structural repair.

(b) Further material characteristics of repair materials for satisfactory durability performance have also been identified. Measurement of these properties for materials proposed for the repair of concrete pavements has enabled their relative performance to be evaluated.

(c) Externally bonded reinforcement is a method which can offer time and cost advantages over other methods for the strengthening of concrete structures. However, the selection of a suitable adhesive is a necessary requisite for satisfactory structural and durability performance.

(d) The structural properties of an adhesive such as strength, modulus of elasticity, creep and fatigue performance are sensitive to both temperature and moisture in-service. Adhesives grades must be selected which are appropriate to the environment in which they will be required to operate.

(e) Finite element stress analysis techniques may be used to gain an understanding of load transfer through patch repairs in reinforced concrete members. The modulus of elasticity of a patch repair material may have a significant influence on the distribution of stress within a repaired beam, particularly in zones of compression stress.

(f) The flexural performance of a beam repaired in a zone of tension stress is enhanced by the use of a relatively high tensile strength repair material. Under sustained loads, the creep deflections of beams may be directly related to the creep characteristics of the repair materials themselves. The fatigue performance of repaired beams is primarily related to that of the steel reinforcement.

(g) Experimental studies of structures repaired under load have demonstrated that it is possible to achieve full composite action across a repaired section. In order to achieve such structural behaviour, care must be taken in the selection of appropriate repair materials and in their application. Grit blasting and water jetting of the substrate concrete are both suitable methods of surface preparation. Given the above conditions, load levels at the time of repair up to and including the full design load do not appear to influence the ultimate behaviour of the repaired structure.

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Table 1. Properties of typical generic patch repair systems

System \ Property	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Compression modulus (kN/mm^2)	Coefficient of thermal expansion ($x10^{-6}/^0C$)	Pull-off strength (N/mm^2)	Shrinkage at 24 hours ($\mu\epsilon$)	Shrinkage from 24 hours to 16 months ($\mu\epsilon$)	Creep from 1 to 16 months at $10N/mm^2$ ($\mu\epsilon$)
Epoxy mortar	69.0	13.7	18.8	36.8	3.87	-170	-50	-720
Polyester mortar	97.3	14.7	24.8	30.1	2.97	-4680	-280	-1380
Acrylic mortar	71.0	10.1	17.9	19.1	2.85	-80	-360	-4210
SBR modified cementitious mortar	79.5	6.5	35.4	10.9	3.09	-920	-740	-430
Acrylic modified cémentitious mortar	29.1	-	32.0	-	1.91	-	-	-
Vinyl acetate modified cementitious mortar	57.8	2.6	18.6	12.0	3.43	-2400	-1060	-2020
Magnesium phosphate mortar	74.3	4.2	49.4	11.9	1.57	+830	+700	-330
OPC/sand mortar	83.0	3.1	26.7	9.4	2.66	-710	-1140	-840
High alumina cement mortar	77.1	4.1	30.6	10.4	1.82	-350	-750	-1240
Flowing concrete	106.3	3.0	40.7	11.5	3.87	-1120	-650	-790
Spray applied mortar	47.0	-	16.6	-	1.84	-	-	-

Table 2. Scoring of typical generic patch systems on durability criteria

System \ Property	Bond to substrate concrete					Compressive modulus	Tensile strength	Development of compressive strength	Permeability		Total percentage score	Ranking
	Effect of curing and service temp.	Effect of thermal cycling	Effect of moisture cycling	Effect of freeze-thaw cycling	Effect of load cycling				Nitrogen gas	Salt solution		
Epoxy mortar	3	10	6	4	5	6	9	5	6	5	59	5
Polyester mortar	2	1	1	2	3	4	10	10	6	1	40	8
SBR modified cementitious mortar	7	4	6	6	7	6	6	1	8	6	57	6
Acrylic modified cementitious mortar	10	8	7	7	8	8	8	4	4	2	66	3
Rapid hardening cementitious mortar	7	8	10	8	9	6	6	3	3	8	68	2
Magnesium phosphate mortar	9	6	4	6	2	4	4	9	8	3	55	7
High alumina cement mortar	1	2	2	3	1	1	1	9	1	8	29	9
OPC/sand mortar	4	3	3	1	4	2	2	2	2	4	27	10
Microsilica concrete	9	5	8	10	10	7	7	7	-	-	79	1
Air entrained concrete	5	10	10	9	6	3	3	6	-	-	65	4

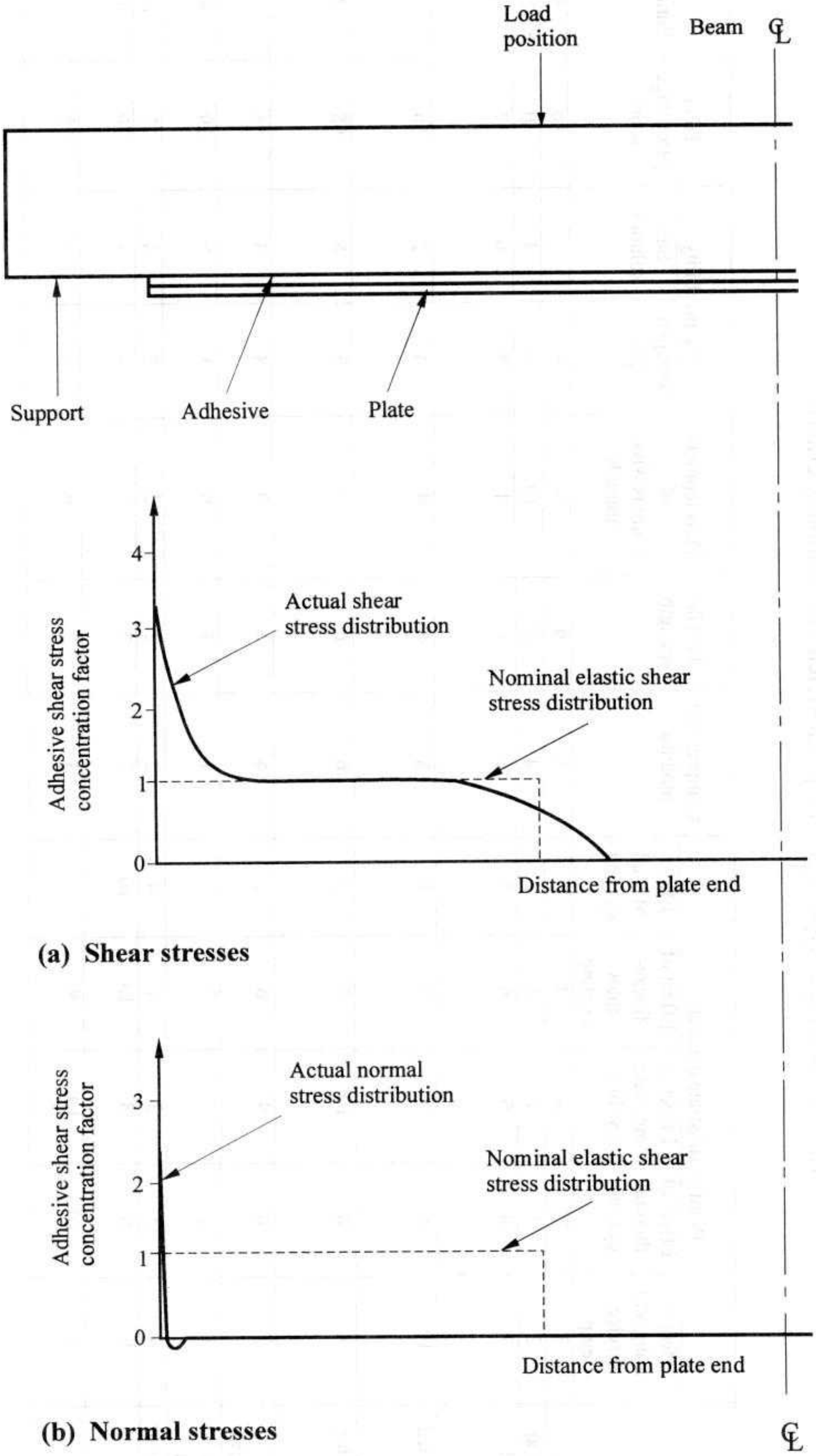
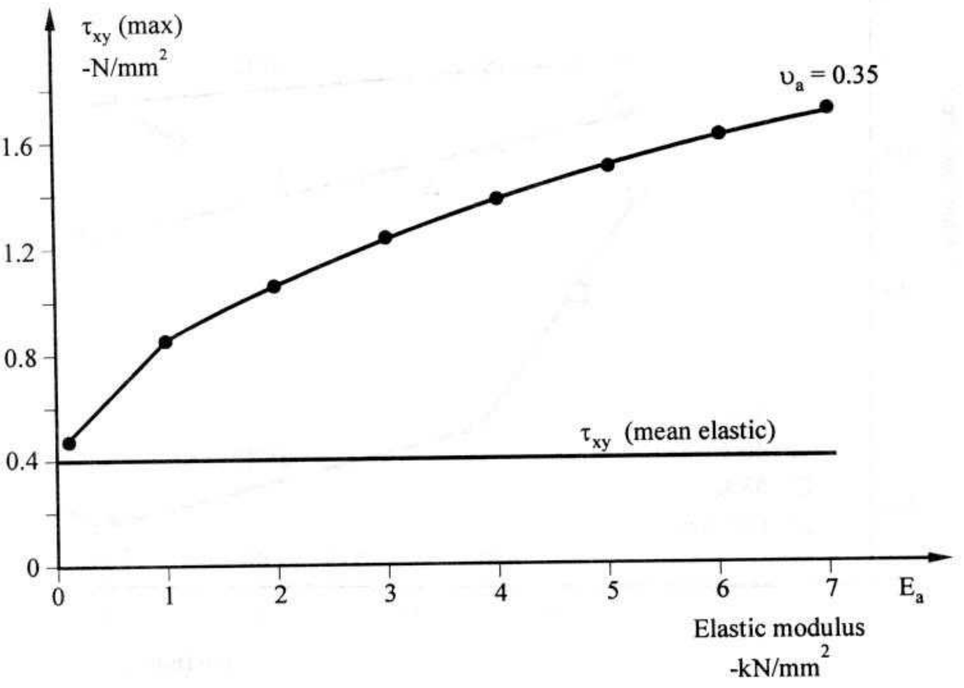
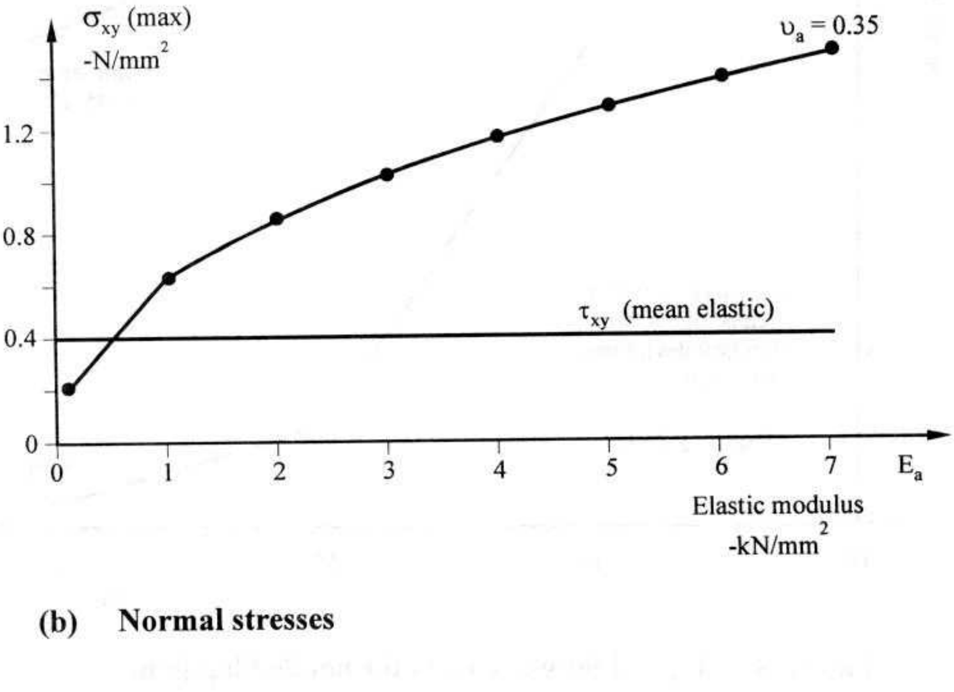


Figure 1 Stress distributions within adhesive layer



(a) Shear stresses



(b) Normal stresses

Figure 2 Effect of adhesive modulus on peak stresses

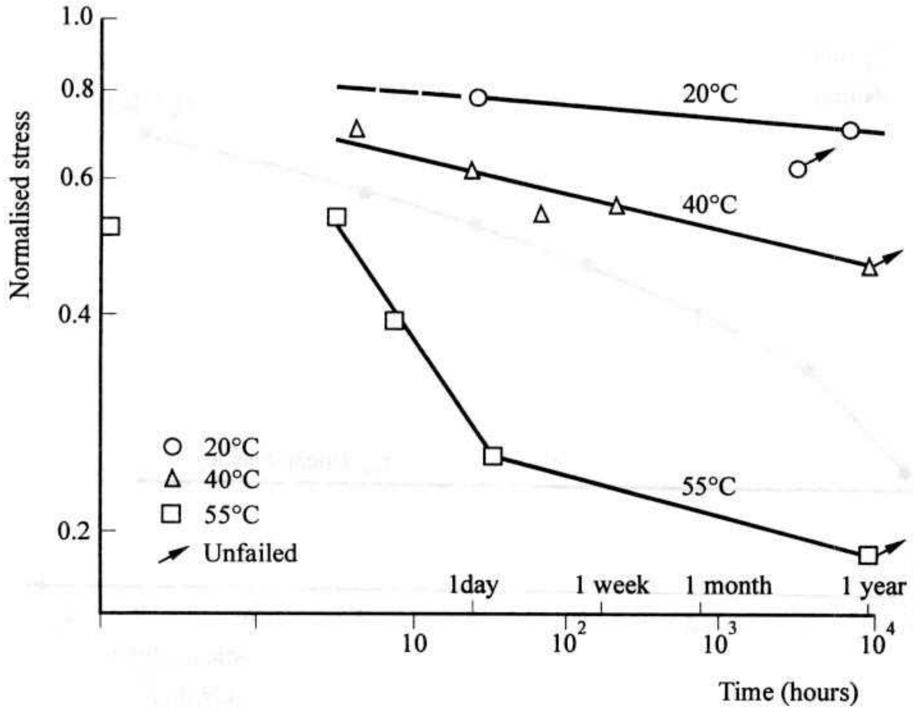


Figure 3 Typical creep curves for bonded lap joints

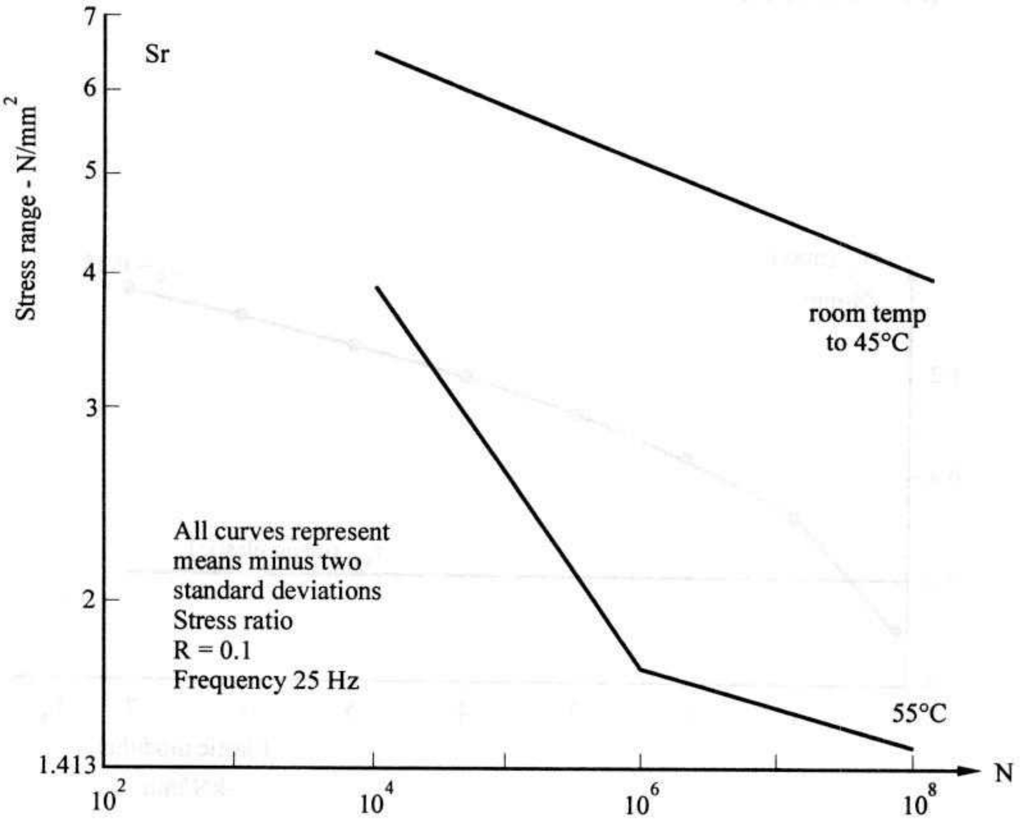


Figure 4 Typical fatigue curves for bonded lap joints

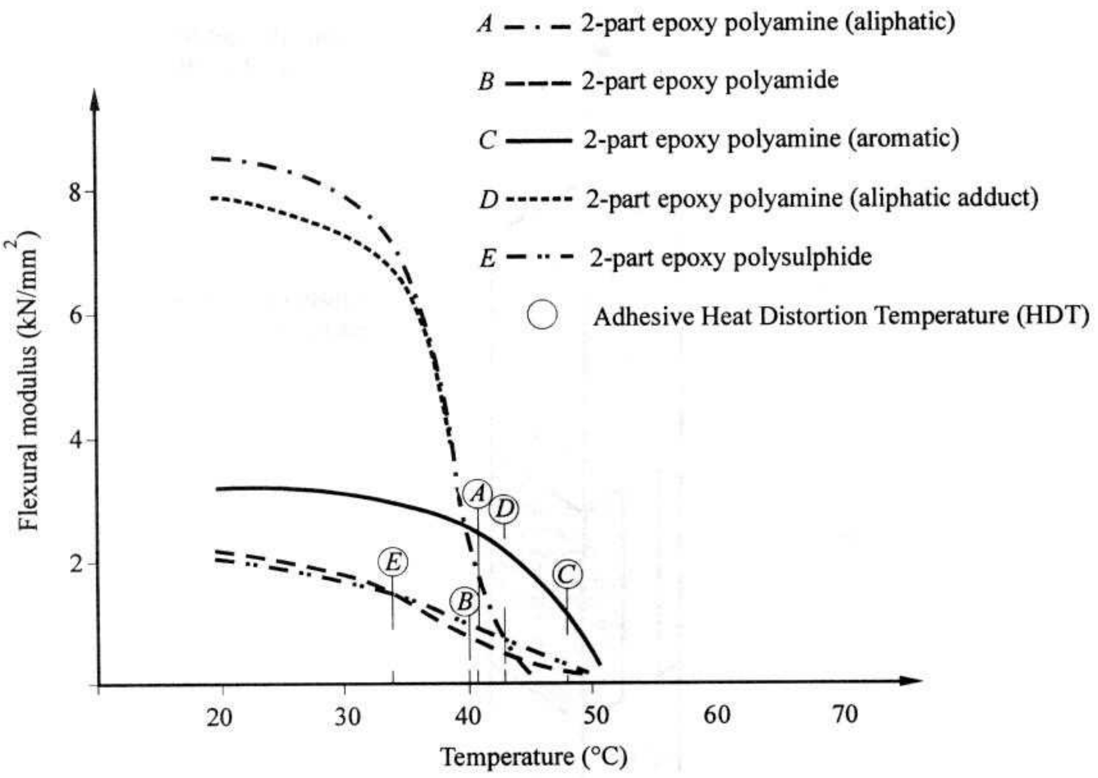


Figure 5 Temperature dependence of bulk adhesive flexural modulus

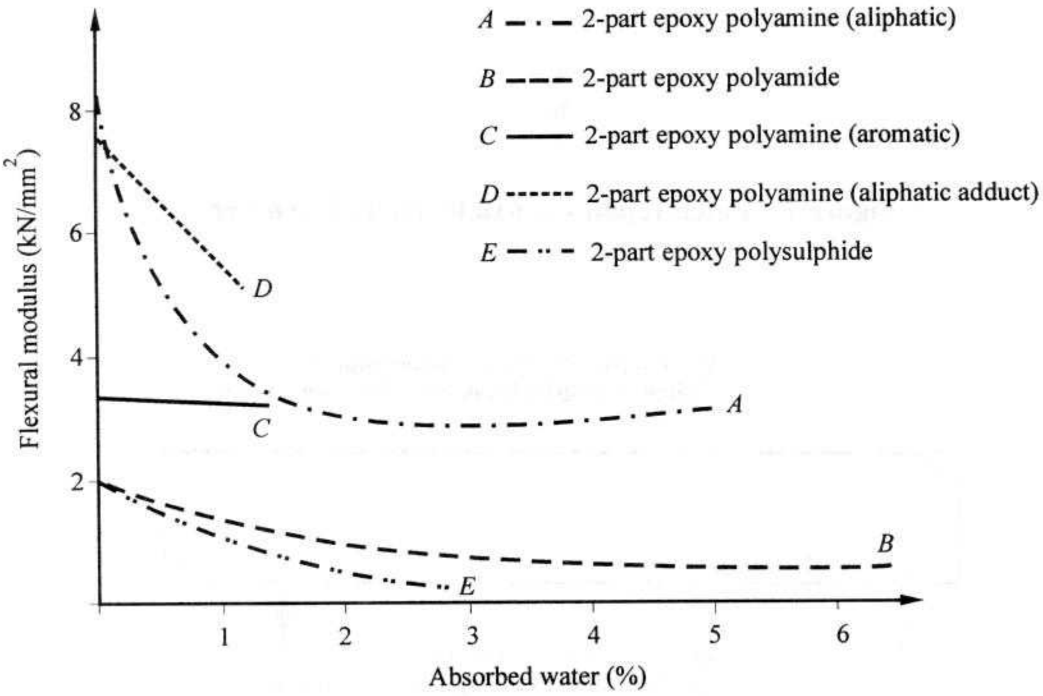


Figure 6 Moisture dependence of bulk adhesive flexural modulus

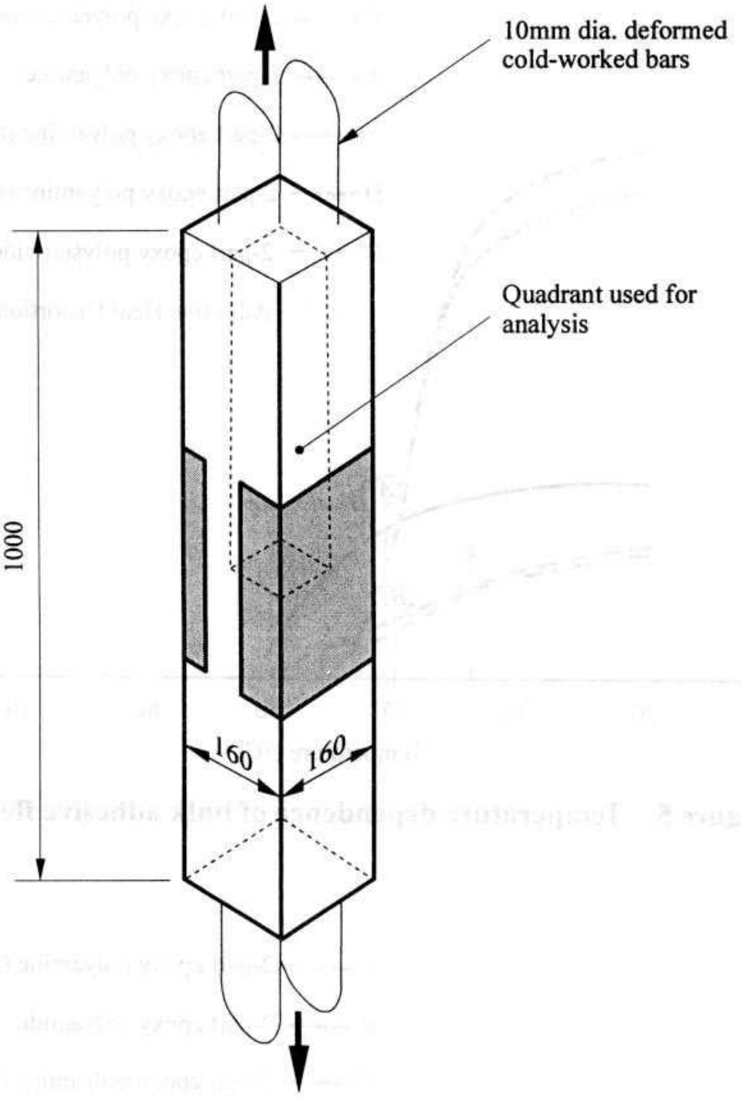


Figure 7 Patch repairs in axially loaded member

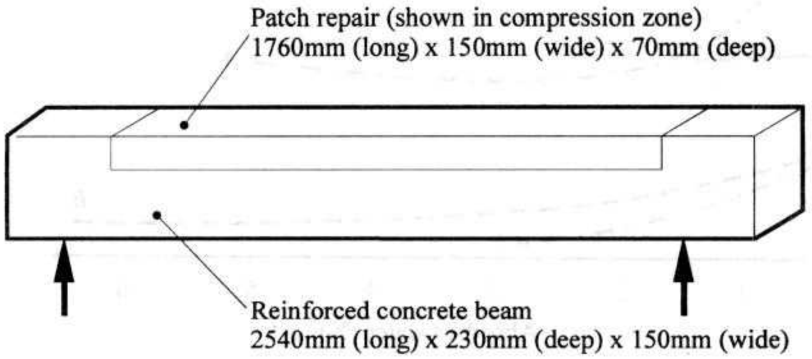


Figure 8 Patch repair in beam element

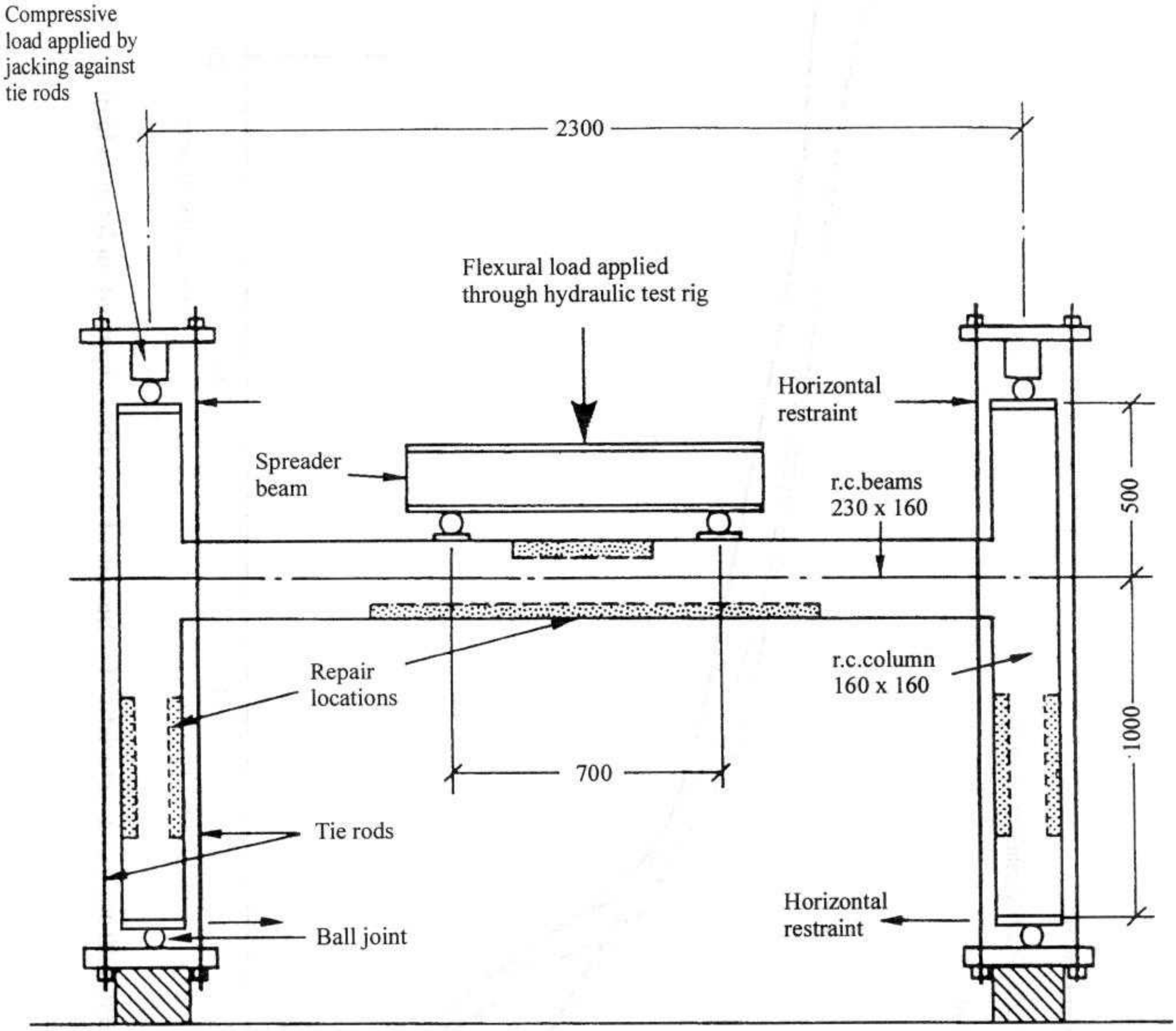


Figure 9 Schematic test arrangement for H-frames

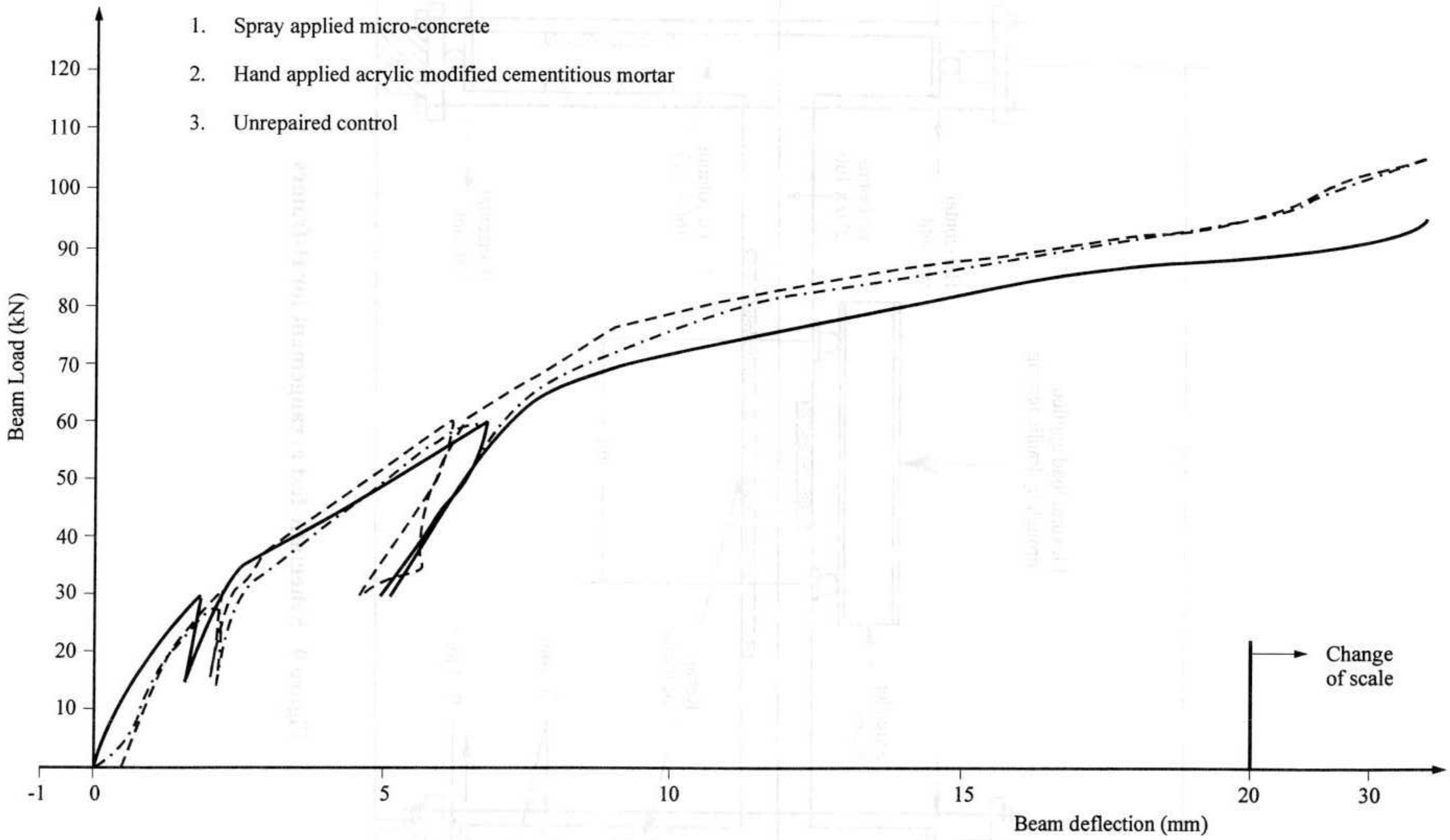


Figure 10 Load deflection characteristics for beams of H-frames repaired under zero load