Strengthening, stiffening and repair of concrete structures

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Strengthening, Stiffening and Repair of Concrete Stuctures

Renforcement et réparation de constructions en béton

Verstärkung, Versteifung und Instandstellung von Beton-Bauwerken

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SUMMARY

A survey is made of techniques for strengthening, stiffening and repairing concrete structures. Such corrective work on existing structures depends for its success on proper planning, and in particular on careful structural assessment. A systematic approach to assessment is suggested, in which the key steps are inspection, diagnosis and prognosis (i.e. assessment of stuctural adequacy). A detailed diagnostic chart is presented as an aid to diagnosis. Methods for strengthening,stiffening and repairing members and assemblages are briefly described, and references are given for further specialised techniques.

RÉSUMÉ

L'article donne un aperçu des méthodes normalement utilisées dans le renforcement et la réparation de structures en béton. Le succès d'une telle intervention dépend essentiellement du soin apporté au relevé de la structure existante et au projet d'assainissement. Un procédé d'évaluation systématique est décrit qui va de l'inspection au diagnostic du comportement futur de la structure. A cet effet, des aide-mémoire sont donnés sous forme de tableaux. Pour rester succinct, des informations détaillées sur des techniques concrètes ne sont pas données, mais peuvent être trouvées dans les références.

ZUSAMMENFASSUNG

Dieser Artikel gibt einen kurzen Überblick über die üblicherweise angewandten Methoden zur Verstärkung und Instandstellung von Bauwerken aus Beton. Der Erfolg einer solchen Verbesserung hängt vorwiegend von einer sorgfältigen Beurteilung des Bauwerkes und einer sauberen Projektierung ab. Es wird ein systematisches Evaluationsverfahren beschrieben, welches die Schritte Inspektion, Diagnose und Prognose über das zukünftige Verhalten des Bauwerks umfasst. Dazu werden Hilfsmittel in Tabellenform gegeben. Detaillierte Angaben über konkrete Massnahmen werden hier aus Platzmangel nicht aufgeführt und können den angegebenen Referenzen entnommen werden.

1. INTRODUCTION

1.1 The Need for Corrective Work in Concrete Structures

Although structural concrete is a relatively durable and maintenance-free form of construction, a significant amount of corrective work has to be carried out during the useful life of many concrete buildings and bridges. In some newly constructed structures, strengthening and stiffening work is needed to eliminate defects which have been caused by errors of design and construction. In older bridges and buildings, repair work has to be undertaken to counteract the effects of normal deterioration, while in some newer construction accelerated deterioration requires major repairs after very few years of service. Specialised techniques of strengthening, stiffening and repair are needed to deal with damage produced by unusual events such as fire, earthquake, foundation movement, impact and overload. Even when a structure successfully outlasts its original economic purpose, extensive reconstruction and rehabilitation are nowadays often preferred to demolition and redevelopment, because of cost advantages.

1.2 Terminology

The techniques which are used for strengthening, stiffening and repairing concrete structures tend to be inter-related so that, for example, the strengthening of a structural member will normally result also in its being stiffened. It is nevertheless useful to distinguish clearly among the various forms of corrective work, and the following terminology is used in this survey:

Repair Work is carried out to eliminate the effects of damage and deterioration and thereby restore a structure to its original 'as constructed' condition.

Strengthening increases the load carrying capacity of an existing structure, and is undertaken in order to eliminate strength inadequacies.

Stiffening is carried out to improve the normal in-service performance of an existing structure, and thereby eliminate inadequacies in serviceability such as excessive deflections, excessive cracking or unacceptable vibration.

Structural Inadequacies which adversely affect strength or serviceability arise from two distinct sources:

(a) from *deficiencies within the structure*, which may be inherent (errors in design or construction) or may develop with time (deterioration, damage);

(b) from *changes in external circumstances* which result in increased and excessive demands on the structure, as for example when a change in use or occupation of a building leads to overloading.

1.3 Structural Assessment and Planning of Corrective Work

Corrective work of a substantial nature should never be carried out in an *ad hoc* manner. It should be carefully planned, and wherever possible the details should be checked by analytic calculations. The most important step in the planning of any strengthening, stiffening or repair work is a careful structural assessment of the existing construction. The purposes of the assessment are to identify all defects and damage, to diagnose their causes, and hence to assess the present and likely future adequacy of the structure [30]. The information obtained from the structural assessment can then be used to determine whether or not corrective work is required and, if so, how it can best be carried out.

Without prior planning and proper assessment, any program of corrective work is likely to prove ineffective. A typical example of repair work which is unsuccessful because of inadequate assessment is the *ad hoc* treatment of active cracks by epoxy resin injection [23]. Unless the causes of cracking and of the subsequent opening and closing of the cracks are identified and eliminated, thereby rendering the cracks dormant, the repaired cracks will almost certainly either re-open or be replaced by adjacent new cracks. In either case the corrective work will be unsuccessful.

1.4 Scope of Report

This report surveys the techniques which are commonly used for strengthening, stiffening and repairing concrete structures. Because of the importance of structural assessment and planning to the success of any corrective work, Section 2 describes a systematic procedure for structural assessment. Specific techniques for the repair of damage are reviewed in Section 3, while methods for strengthening and stiffening individual members and structural assemblages are considered in Section 4.

In order to achieve brevity in this review report, much detailed information on specialised techniques has been omitted. However, further details can in most cases be obtained from the references, which have been selected to provide a broad coverage of the field.

2. STRUCTURAL ASSESSMENT

As already noted, the purpose of the structural assessment is to determine the adequacy, or otherwise, of the structure at present and in the foreseeable future. The assessment procedure is essentially one of detection (of defects and damage), diagnosis, and prognosis [30].

Proper structural assessment is likely to be time consuming and expensive, and may sometimes appear to be unwarranted, especially when the in-service behaviour of the structure is satisfactory. In the case of superficial, routine repairs, this may be so. However, when more extensive work is to be undertaken, such as structural modifications, it should be remembered that service load behaviour may give no hint at all of potential problems such as progressive collapse or instability. Hidden potential problems will be discovered only by careful, systematic assessment.

2.1 Assessment Errors

Errors of two main types can occur in the assessment of structural adequacy. By analogy with the standard errors of statistical hypothesis testing and quality control, they may be described as Type 1 and Type 2 errors:

A *Type 1 error* occurs when the structure is assessed, incorrectly, as being inadequate, thereby incurring unnecessarily the costs of corrective work.

A *Type II error* is made if the structure is assessed as adequate when it is not, so that property, and possibly life, are endangered.

2.2 Assessment Procedure

Assessment errors are most likely to occur in the diagnosis and prognosis stages, mainly because these activities are inductive in nature. In the case of concrete structures, diagnosis is particularly difficult because there are relatively few symptoms of structural inadequacy, but relatively many likely causes.

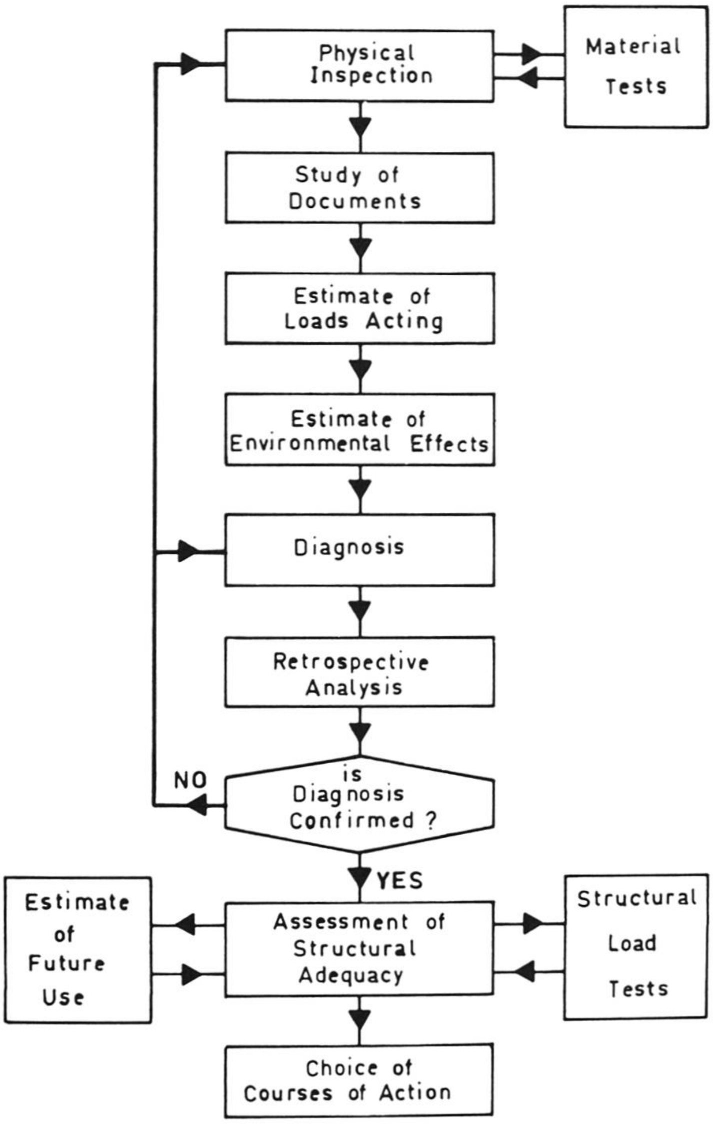


Fig. 1: Assessment Procedure

To minimise the likelihood of errors in assessment, a scientific, self-checking approach should be adopted. Such a procedure is shown in Fig 1 in the form of a flow diagram. In essence a tentative diagnosis is made on the available information, and is then confirmed (or rejected) by restrospective analysis of structural behaviour and, if appropriate, by re-inspection of the structure.

The assessment of structural adequacy, ie prognosis, must rely partly on predictive analysis and, to some extent, on subjective evaluation. In appropriate conditions, limited confirmation of a prognosis or assessment can be obtained by conducting suitable load tests.

Although structural assessment has received some attention previously [12,10,30], it will be appropriate to discuss briefly the main steps indicated in Fig 1:

2.2.1 Physical Inspection

The first step in assessment is a careful physical inspection of the structure, to observe all symptoms of damage and defect, such as spalling of concrete, excessive cracking, large deflections, etc. The symptoms may be associated with the concrete, with the steel, or with entire members. A list of common symptoms of defects and damage is given in Table 1, together with their most common causes.

During the inspection, details of crack patterns will normally be recorded and deflections and relative movements within the structure may need to be measured. If time, temperature or sequences of loading and unloading are likely to be important influences, the physical inspection should continue over a sufficiently long period of time to pick up cyclic changes in deflections, crack widths, etc.

The physical inspection should also be used to obtain useful information on the quality of the original construction work. Evidence of construction deficiencies such as honeycombing, segregation, permeability of the concrete and misplacement of reinforcement should be sought. In some cases, samples of concrete and reinforcing steel may need to be taken for physical testing or chemical analysis. In other cases, detecting equipment may be required for the location of the reinforcing steel in the members.

2.2.2 Study of Documentation

The available documentation on the design and construction of a building or bridge can provide useful information for the detection of hidden defects and for the diagnosis of structural inadequacy. Additional documentation concerning the in-service history of the structure can be helpful in explaining unexpected damage and cracking, especially when abnormal events have occurred, such as the demolition or collapse of an adjacent structure, earth tremor, etc.

2.2.3 Estimation of Loads and Environmental Conditions

The loads acting on a structure often bear little resemblance to the loads used in the design calculations, and unexpected cracking and damage can sometimes be explained by forces or load combinations which were not considered at the design stage. On the other hand, actual loads are often far less severe than the standard design loads. If *de facto* structural adequacy can be demonstrated on the basis of actual loads being less severe than the design values, expensive corrective work may well be avoided.

Environmental effects such as extremes of temperature or an aggressive atmosphere can often explain a range of serviceability problems such as separation cracking in roof slabs or deterioration of exposed concrete surfaces. Foundations are an important part of the environment of a structure, which rarely act as assumed in the design calculations. In extreme situations, for example where some expansive soils are involved, apparently irrelevant details such as landscaping and tree planting can have an important effect on the behaviour of foundations of quite substantial buildings [20].

2.2.4 Diagnosis

The most difficult step in structural assessment is frequently found to be the diagnosis of the causes of damage and structural inadequacy. It is emphasised that in Table 1 only the most common causes are listed against the symptoms. A more detailed (but not exhaustive) diagnostic chart, given in Table 2, relates symptoms to general categories of causes and thence to possible specific causes [30].

Diagnosis is essentially inductive and relies to some extent on experience and intuition. It is therefore liable to serious error. An initial, tentative diagnosis should be made from the assembled information, and should then be confirmed by retrospective analysis and, if necessary, by re-inspection, material testing or even load testing, before any corrective work is undertaken.

2.2.5 Retrospective Analysis

The retrospective analysis is undertaken to confirm the correctness of the diagnosis: it should show that the observed symptoms indeed follow from the postulated causes. The analysis should also predict, with believable accuracy, any measurements (crack widths, deflections, etc) which may have been made. The analysis will be based on actual loads, material properties and structural geometry, rather than nominal design values.

In some cases the analysis may be extended to predict the effect of defects or damage on potential structural behaviour, and hence to evaluate the likely future performance of the structure.

2.2.6 Assessment of Structural Adequacy (Prognosis)

Although the structural assessment will be made from all of the assembled information, the final evaluation frequently requires some subjective judgement concerning the levels of safety and serviceability which should be accepted [26]. In the case of an existing structure, code design criteria concerning safety against collapse, deflection limits and crack widths can at best be regarded as rough guidelines to structural adequacy. An existing slab floor with well defined loads may thus be assessed to have adequate strength, even when the live load factor against failure is well below the relevant code figure. On the other hand, the same floor may justifiably be assessed as unserviceable if it is excessively springy, even when all the deflection criteria and other code requirements are satisfied.

2.2.7 Load Tests

Load testing is shown in Fig 1 as a further method of obtaining useful information to assist in (or to confirm) structural assessment. Although load tests can prove to be expensive, especially when the structure has to be taken out of service, this may be the only way of achieving empirical confirmation of an assessment.

Standard procedures for load testing of structures are usually specified in relevant codes of practice; nevertheless, it is important to realize that such tests are rarely a realistic approximation of in-service conditions. Vertical test loads are used to approximate mild overloads which would, in reality, occur either simultaneously or sequentially with horizontal loads, foundation movements and temperature changes. The possibility of interactive effects should always be considered, and careful interpretation of the results of the load test is therefore required.

Acceptance of a structure which performs satisfactorily under a standard load test should not be automatic. Rather, the details of the load test should be carefully chosen to properly test structural adequacy.

2.3 Post-Assessment Action

When structural adequacy has been assessed, appropriate courses of action need to be decided on and corrective procedures have to be planned. Depending on the severity of the damage and defects in the structure, one of the following actions may be appropriate:

(a) do nothing (the structure has been assessed as adequate);

(b) no corrective action is taken, but the structure is monitored for signs of deterioration (wait and see policy);

(c) corrective work is undertaken, but the structure is not taken out of service;

(d) the structure is taken out of service temporarily, and corrective work is carried out;

(e) the structure is taken out of service indefinitely and the alternatives of demolition and reconstruction are considered.

3. REPAIR METHODS

The repair operations which are most frequently undertaken on concrete structures are the removal and replacement of damaged or deteriorated concerete, the treatment of excessively cracked regions of concrete and the replacement of rusted or damaged steel reinforcement. More complex repair operations which involve entire structural components or assemblages are difficult to distinguish from the strengthening and stiffening operations which are considered in Section 4 of this report.

3.1 Concrete Replacement

Damaged or deteriorated regions of concrete can usually be repaired by:

(a) cutting back and removing all affected concrete;

(b) treating the exposed surface of the remaining concrete to improve composite action with the replacement material; and

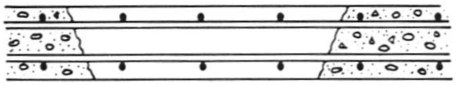
(c) replacement with new material which will better withstand the conditions which have led to the problem.

Such repairs are often referred to as *full depth patching* when the full thickness of concrete is replaced (Fig 2a) and *surface patching* when only the surface layer is replaced (Fig 2b). An additional step in the repair operation which often is advisable is the removal of the primary cause of damage or deterioration. Alternatively, additional surface protection of the repaired concerete may be attempted.

In the cutting back operation, the affected concrete and delaminated layers are removed by pneumatic hand tool or hammer, to leave only sound concrete. Square or slightly inclined, but reasonably straight, interfaces should be used as shown in Fig 2. In the case of surface patching, the depth of patch should be at least 40 to 50 mm if concrete is to be used as the repair material[24].

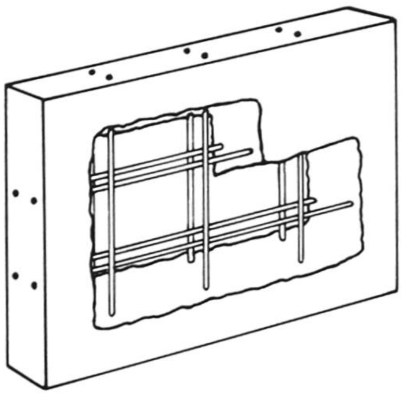
Ideally, the repair material should have stiffness and thermal properties which match closely those of the original concrete It should also have low shrinkage, and be resistant to any effects which may lead to renewed damage or deterioration. Low-slump, high strength concrete with a high aggregate content and low total water content is usually a suitable repair material. Latex modification can be used to reduce the water cement ratio, while epoxy resin compounds and polymer concretes may be useful when curing is impractical [2].

Patching of large vertical surfaces and of the underside of horizontal members may be carried out with sprayed gunite (shotcrete), which is applied in layers, with a careful check for drumminess being made on each layer [17,13,23].



(a) Slab — full patch

(b) Slab — surface patch



(c) Wall — full patch

Fig. 2: Concrete Replacement

If the replacement material is to be plain concrete, the exposed surface of sound concrete should be first moistened and then treated by scrubbing or brushing with grout. Alternatively, if the repair material is to be a resin-modified concrete, an epoxy resin bonding agent will be used. If gunite is to be used, no bonding coat of mortar should be applied. Exposed reinforcement should be cleaned of loose rust and active corrosion spots and can also be treated with bonding material.

3.2 Steel Replacement

When steel reinforcement corrodes to any extent, the surrounding concrete cover tends to crack and split. The cracks are caused by internal bursting stresses which occur in the concrete around the bars because of a net increase in volume of the corrosion product. A minute loss of effective cross-sectional steel area by corrosion is usually sufficient to cause serious deterioration of the surrounding concrete. For this reason, the steel is relatively intact in most regions which require concrete patching, and replacement of reinforcement is rarely necessary.

Only in older buildings which have been neglected over a period of years is it usual to find regions of exposed reinforcement deteriorated to a sufficient extent to warrant replacement. In such structures, it may be necessary to undertake strengthening and stiffening of entire members, possibly with the complete replacement of seriously affected components.

When reinforcing bars have to be replaced, the portion to be removed should be large enough to include all active corrosion spots. Special mechanical splices can be used to ensure adequate anchorage of the replacement [24,31].

3.3 Repair of Cracks

Epoxy resin injection techniques are now widely used for the repair of cracks in concrete structures, and have largely replaced more doubtful techniques such as stitching and blanketing [21]. As epoxy injection is a specialised operation which is adequately described in trade literature, it will not be necessary to consider the detailed steps here.

It has already been noted that repair by epoxy injection is only likely to be effective if the cracks are dormant. For this reason, crack widths should be measured over a period of time before any repairs are attempted, to check for movement. Such measurements should be undertaken at the inspection stage of assessment. If variations in crack widths are detected, and epoxy injection is to be undertaken, cracks must be rendered dormant, either by removing the underlying cause or possibly by cutting control joints at key sections. With structural movement controlled, injection repair can be very effective [22].

Epoxy injection techniques can also be used to repair crushed and spalled regions of concrete, and hence to repair structures which have actually failed. Provided the reinforcing steel is in good condition, it is often possible to prop the structure into its original shape, and extensively inject and repair the damaged concrete and hence achieve complete rehabilitation. Such repairs can be quite spectacular [22,7].

The epoxy injection repair of dormant cracks has some disadvantages. Besides being an expensive and specialised technique, the injected material has poor fire resistance and tends to brittleness in cold weather. Injection of cement grout is therefore a viable alternative to resin injection and may be preferred if the cracks are wide (eg in excess of 5 mm) or if fire resistance or resistance to large temperature fluctuations are important considerations.

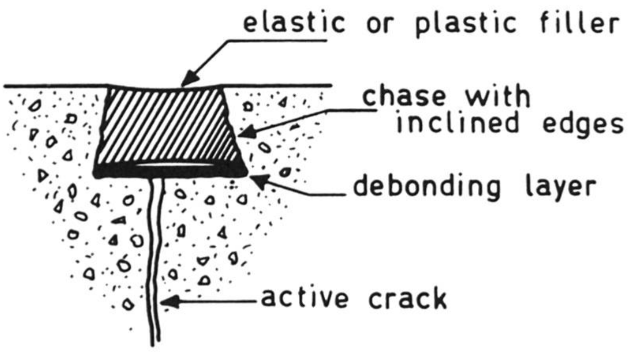


Fig. 3: Repair of Active Crack

Although special repair procedures have been developed for treating active cracks, they become less effective as the amount of movement in the crack increases [6]. Variations in crack width are allowed for by means of elastic or plastic fillers which are placed in grooves sawn into the concrete at the crack (Fig 3). The width of extensible filling material, and hence the width of the repair groove, should be sufficient to cater for the expected movement between the faces of the crack. Such repairs are unsightly, and tend to be ineffective when the crack is wide. Plastic filled water bars in repairs of this type are likely not to be effective over long periods of time. When large movements occur, the only alternatives appear to be either to remove the structural cause of movement or to camouflage the entire region by blanketing.

The introduction of prestressing force by means of external cables or flat jacks is another alternative to be considered for closing the cracks and hence eliminating altogether the problem of crack repair.

4. STRENGTHENING AND STIFFENING OF MEMBERS

Stengthening or stiffening of members such as columns and girders is usually achieved either by replacing poor quality or defective material by better quality material, or by adding additional material to the member. In either case, the new material will usually be reinforcing steel, high quality concrete, thin steel plates and straps, or various combinations of these materials. The main difficulty in this type of operation is to achieve continuity of structural action between the original material and the new material. Various techniques of bolting, gluing, dowelling and keying have been developed to provide positive force transfer and composite action.

Other procedures may prove to be appropriate in certain circumstances. For example, stiffening, and to a very limited extent, strengthening, of flexural members can sometimes be achieved by external prestressing.

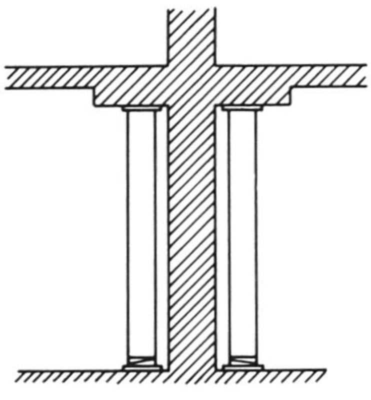


Fig. 4: Propping of Column

4.1 Column Strengthening

One of the simplest and most effective methods for strengthening a column in an existing building is to partially unload the column, by jacking between floors, and then insert two or more props to carry portion of the axial load (Fig 4). The props are usually rolled steel sections which may subsequently be encased in concrete to improve fire protection and appearance. The disadvantages of this procedure are that considerable floor space is lost, and that the props may not be effective in transferring moment unless positive connection details are introduced at both ends, for example in the form of end plates bolted through holes drilled in the floors.

Additional axial strength can be provided to a column by 'sleeving' (Fig 5a). The sleeve consists of additional longitudinal and horizontal steel tied or ramsetted to the existing column, and with a cast-in-place concrete or gunite cover. Several variants, described by Westerberg [31] are shown in Figs 5b and 5c. Construction difficulties occur in the extreme upper region of the sleeve, where weak areas are likely to exist. The moment connection in this region is also poor, because the added reinforcement is terminated here. Some moment continuity at the column ends can be achieved by extending the additional reinforcement

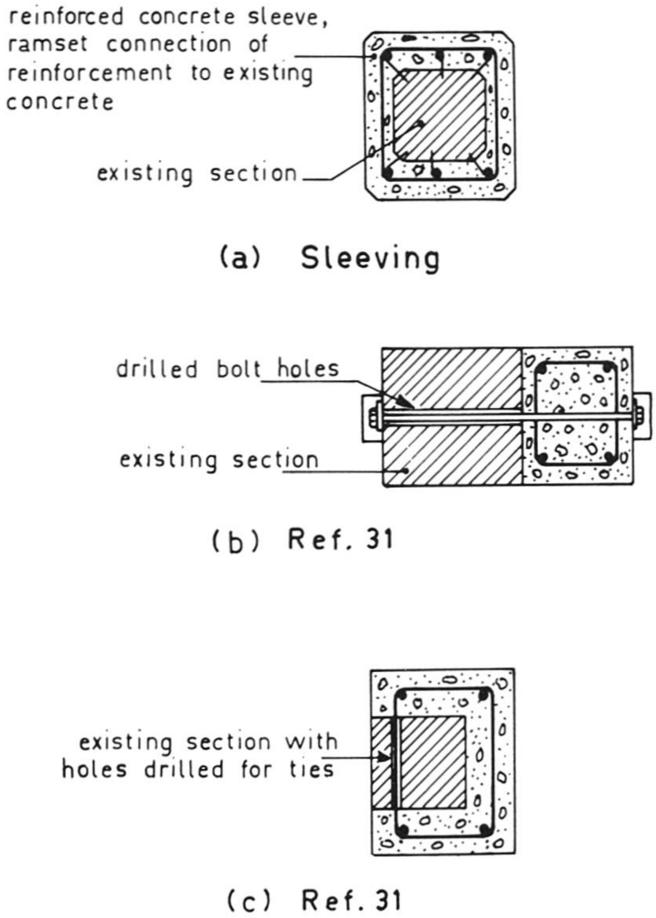


Fig. 5: Column Strengthening

through holes drilled in the floors, or by carefully removing and replacing portion of the adjacent floor concrete to ensure continuity of the new reinforcement. A simpler, cheaper, but aesthetically less pleasing means of providing moment transfer is to introduce a steel collar which fits snuggly to the column and to the underside of the upper floor, and which is bolted or glued to both (Fig 6).

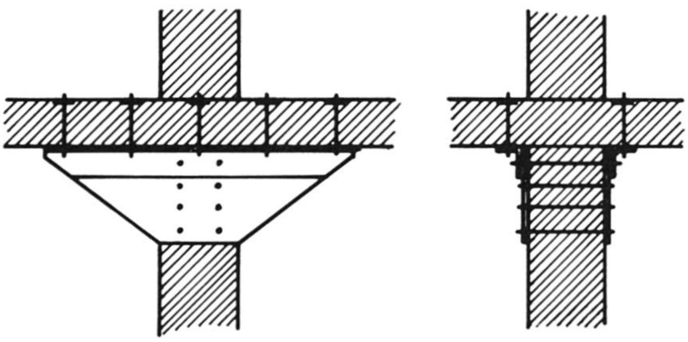


Fig. 6: Steel Collar for Moment Transfer

During the strengthening operations, the column should be partially unloaded so that the total axial load is finally shared between the new and old construction materials.

4.2 Strengthening and Stiffening of Beams and Girders

Commonly used methods for strengthening and stiffening flexural members include:

(a) provision of additional concrete on the compressive face (Fig 7a);
(b) addition of tensile reinforcement with a cast-in-place or gunited cover (Fig 7b);
(c) bolting or gluing steel plates or straps to the surface of the member (Fig 7c).

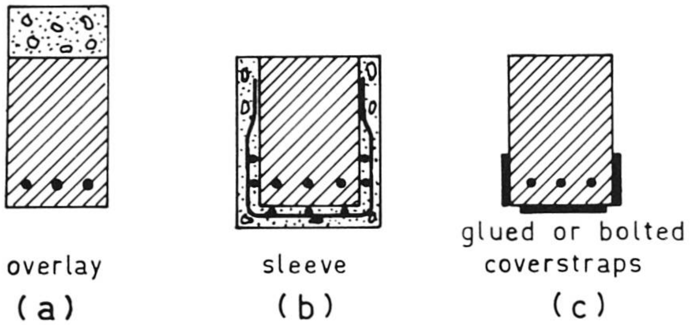


Fig. 7: Strengthening and Stiffening of Flexural Members

As in most strengthening, stiffening and repair operations, the main problem is to ensure good composite action between old and new material. Bolting of new concrete or steel to the existing member is effective, but is expensive and time consuming, as holes usually have to be drilled through the old concrete (Fig 7c). For this reason, gluing procedures have been recently developed which appear to provide strong and durable connections between concrete and surface straps and plates [19]. The gluing process has been used successfully in the recent repair and strengthening of an exposed bridge pier in Western Australia [22].

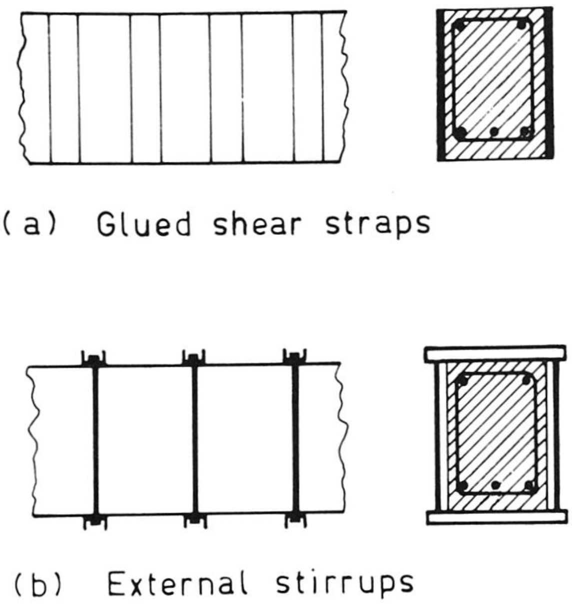


Fig. 8: Shear Strengthening

Side plates can also be used to strengthen girders in shear (Fig 8a). Alternatively, external stirrups (Fig 8b) are a simple, inexpensive, but unsightly, method for increasing the shear capacity of a girder.

Whenever steel is externally bolted or glued to a member, consideration should be given to a final coat of guniting to improve the appearance of the member and to provide some protection to the steel.

4.3 Strengthening and Stiffening of Slabs

Stiffening is not infrequently required to reduce unacceptable vibrations and deflections in slab floors which have adequate strength. The simplest and cheapest procedure is to introduce additional props either in-span or in the vicinity of existing columns and walls. However, this solution will often be unacceptable for architectural reasons, even though props placed quite close to existing columns may be sufficient to bring the structure to an acceptable standard of serviceability.

If the required increase in stiffness is not too great, stiffening steel collars around the heads of supporting columns can be effective. They must be rigidly connected to the floor and to the column so that the effective span of the floor is decreased. The potential effectiveness of collars, and hence their required size, can be checked by means of deflection calculations for the slab.

Underlays, consisting of additional tensile reinforcement fixed to the existing concrete by bolts or ramsets and with a gunite cover, have been used to increase both the stiffness and the strength of existing floor systems [6]. The success of the underlay depends on the skill with which the guniting is carried out, and will often be used as a last resource, for example for the repair of a fire damaged floor. Subsequent drilling and bolting through the new floor system at regular spacings can ensure good composite action and guarantee success of this method.

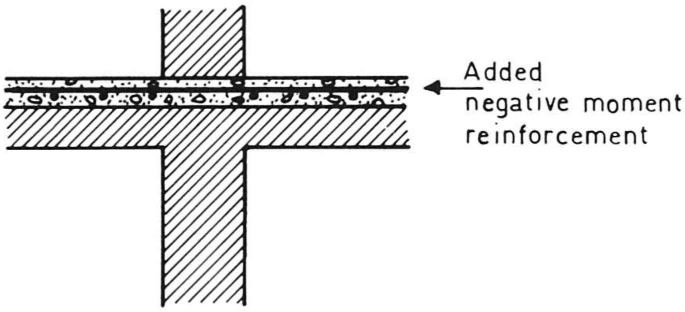


Fig. 9: Slab Overlay

An overlay of new concrete on top of an existing floor system can also be used with prospects of excellent composite action between old and new materials. Tensile reinforcement should be introduced in all negative moment regions (adjacent to columns and wall supports) to increase load capacity and control crack widths in the new layer (Fig 9).

In the case of both the overlay and the underlay, the self-weight of the floor system will be significantly increased; check calculations should therefore be made to confirm that the benefits of such corrective work will be more than marginal.

In some circumstances, a significant increase in the load capacity of a slab system has to be achieved. A completely new slab can be cast, with positive and negative reinforcement, on top of the existing slab. Calculations of strength and deflection can be made by assuming conservatively that no composite action exists and that the old and new slabs contribute additively to strength and stiffness. This solution is obviously only feasible where head room and floor level do not become limiting architectural considerations.

4.4 Member Replacement

In all of the situations discussed here, an effective but extreme solution is to completely replace the particular member. Replacement is obviously time consuming and expensive. It can cause extensive disruption in the use of the building on various floors because of the need for temporary propping. However, the procedure is effective provided proper care is taken to achieve continuity of reinforcement. It should be considered as a last resort when the reliability and effectiveness of the less drastic approaches are open to question. Clearly, selelective replacement of entire structural components will be necessary in buildings which have been severely damaged, for example by blast, fire or earth tremor.

4.5 Prestressing

External prestressing tendons are frequently used to repair and stiffen sagging flexural members such as roof girders in buildings. If the tendon is suitably kinked, it can be used to 'balance' portion of the applied load or self-weight load. The balanced load is thus transferred by tensile force in the tendon to the supports of the member, which is then left essentially in uniform compression (Fig 10).

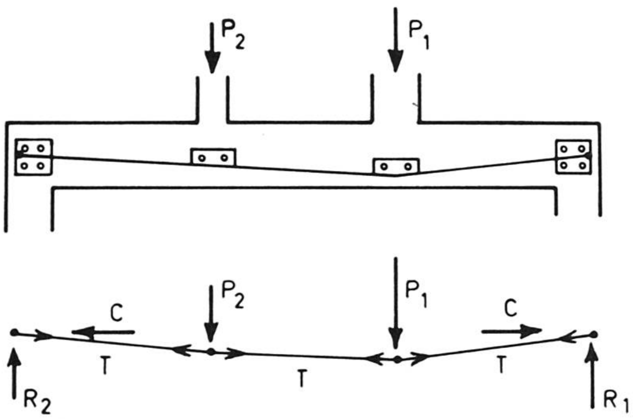


Fig. 10: Load Balancing with External Prestress

Although external prestressing operations are efficient in repairing and stiffening flexural members, they are not always so effective in improving ultimate strength. The subsequent guniting or grouting which is used to protect the tendons from fire and corrosion are not always effective in providing bond between the tendon and the existing concrete surface, so that the overload behaviour may be more like that of an ungrouted post-tensioned member.

Prestressing is an effective means of tying members together, improving connections in a building, and ensuring structural integrity. An interesting example of the use of prestressing to tie the body and tower of a church together, to circumvent problems of non-uniform foundation movement, is reported by Delisle [9]. Applications of prestressing in the treatment of distressed structures have been discussed by Kar [16].

4.6 Strengthening and Stiffening of Assemblages of Members

Strengthening and stiffening operations which involve assemblages of members or even the entire structural system tend to be straightforward if the requirement is to replace existing members or to introduce additional members. On the other hand, structural modifications sometimes require the removal of some key structural members and the re-arrangement of the load carrying mechanisms. This occurs, for example, when some of the ground floor columns in an older building are removed to create larger areas of open space. In such cases, difficult design and analysis problems often demand ingenious solutions. Load balancing by means of external prestressing cables is one of the most effective methods of transferring forces to supports without increasing significantly the moments in existing flexural members (Fig 10). This technique has thus been used effectively in the rehabilitation of various buildings.

The strengthening and stiffening problems which arise from structural assemblages are often unique and require 'one off' solutions. They are best reported individually in the form of case studies and will not therefore be discussed in this review.

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TABLE 1: SYMPTOMS AND LIKELY CAUSES:
DEFECTS AND DAMAGE IN CONCRETE STRUCTURES

SYMPTOMS	LIKELY CAUSE
1. ACTIVE CRACKS	
1.1 Vertical cracks	excessive moment
1.2 Inclined cracks	excessive shear or torsion
2. DORMANT CRACKS	
2.1 Vertical or inclined	temporary overload
2.2 Separating crack extending completely through member	restrained shrinkage, or restrained temperature
2.3 Cracks at change in cross-section	local stress concentrations
2.4 Cracks at change in shape of structure	lack of control joints
2.5 Isolated flexural crack in region of low moment	bar cut-off acting as crack starter
2.6 Dormant surface cracks	plastic setting, poor curing, loss of surface water, windy conditions at time of casting
3. SCALING AND SPALLING OF CONCRETE	excessive compressive stress, chemical attack
4. SWELLING OF CONCRETE	alkali-aggregate reaction
5. DISCOLORATION OF CONCRETE	chemical attack, fungus growth, rusting of steel
6. EROSION OF CONCRETE SURFACE	abrasion, chemical attack, permeable concrete
7. RUSTING OF STEEL	permeable concrete cover, stray electrolytic currents
8. YIELDING OF STEEL	overload
9. SNAPPING OF STEEL	fatigue, brittle fracture
10. EXCESSIVE DEFLECTION OF MEMBER	overload, foundation movement, inadequate or incorrectly placed reinforcement

TABLE 2: DIAGNOSTIC CHART

GENERAL CAUSE	SPECIFIC CAUSE	SYMPTOMS IN: CONCRETE: ACTIVE CRACKS	CONCRETE: DORMANT CRACKS	CONCRETE: SPALLING	CONCRETE: SWELLING	CONCRETE: DISCOLORATION	CONCRETE: SURFACE EROSION	STEEL: RUSTING OF STEEL	STEEL: YIELDING OF STEEL	MEMBER: EXCESSIVE DEFLECTION: SHORT TERM	MEMBER: EXCESSIVE DEFLECTION: PERMANENT
1 CONCRETE TECHNOLOGY	1.1 CONTAMINATED WATER (salt water oils)					X	X	X			
	1.2 CONTAMINANTS IN CONCRETE (sawdust)					X	X	X			
	1.3 INAPPROPRIATE ADMIXTURES (low F_c')							X			
	1.4 EXPANSIVE AGGREGATES			X	X						
	1.5 ALKALI-AGGREGATE REACTION	X		X	X						
	1.6 POOR SURFACE FINISHING						X	X			
	1.7 PERMEABLE CONCRETE					X	X	X			
	1.8 LOW TEMPERATURE DURING POUR			X			X				
2 ENVIRONMENTAL EFFECTS	2.1 CARBONIC ACID (dairies, breweries)						X				
	2.2 HYDROGEN SULFIDE (sewers)						X				
	2.3 SULPHATE ATTACK				X		X				
	2.4 FLUE GASES					X	X				
	2.5 WAVE ACTION, WATER FLOW, CAVITATION						X				
	2.6 CYCLES OF FREEZING AND THAWING						X				
	2.7 CYCLIC WETTING AND DRYING				X		X				
	2.8 CYCLIC CHANGES IN TEMPERATURE (diurnal and/or seasonal)	X	X								
	2.9 ELECTROLYTIC ATTACK	X		X				X			
3 FOUNDATION PROBLEMS	3.1 SETTLEMENT										X
	3.2 DIFFERENTIAL SETTLEMENT	X	X	X					X		X
	3.3 LATERAL GROUND MOVEMENT	X	X	X							
	3.4 HEAVING	X	X	X							X
	3.5 FROST			X			X	X			
4 CONSTRUCTION ERRORS	4.1 FORMWORK PROBLEMS (lack of strength and stiffness, lack of bracing, premature removal)		X	X							X
	4.2 POOR CONCRETE STRENGTH (added water, batching errors, incorrect or inappropriate mix, etc)	X		X			X			X	X
	4.3 INADEQUATE CURING OF CONCRETE (low strength, high shrinkage, high creep)	X		X							X
	4.4 EXCESSIVE VIBRATION (mix segregation)		X				X				
	4.5 OVERSIZE POURS (differential setting)		X	X							
	4.6 INCORRECT GRADE OF STEEL	X							X		X
	4.7 INCORRECT LOCATION AND QUANTITY OF STEEL	X							X	X	X
	4.8 OVERLOADS DURING CONSTRUCTION		X	X					X		X
5 DESIGN ERRORS	5.1 LOAD UNDER-ESTIMATED	X		X					X	X	X
	5.2 STRENGTHS OVER-ESTIMATED	X		X					X		X
	5.3 STIFFNESS OVER-ESTIMATED	X								X	X
	5.4 OMISSION OF CONTROL JOINTS	X	X								
	5.5 INADEQUATE TREATMENT OF INELASTIC EFFECTS	X	X								X
	5.6 INACCURATE OR INAPPROPRIATE METHOD OF STRUCTURAL ANALYSIS	X		X					X	X	X
6 DETAILING ERRORS	6.1 ERRORS IN TRANSFER OF INFORMATION TO DRAWINGS	X		X					X	X	X
	6.2 STEEL CONGESTION		X								
	6.3 SHARP CHANGES IN DIMENSIONS ALONG MEMBERS	X	X	X							
	6.4 BAR TERMINATION	X	X								
	6.5 INADEQUATE COVER		X					X			
	6.6 ANCHORAGE PROBLEMS	X	X	X							
7 BUILDING TECHNOLOGY	7.1 TEMPERATURE EFFECTS (cold storage, airconditioning)	X									
	7.2 CLADDING (method of connection to frame, strength and durability)		X								
	7.3 INADEQUATE DRAINAGE (omission of drainage gradients; inadequate drains, drip groove omitted)					X	X				
	7.4 INADEQUATE WEARING SURFACES (for fork-lift trucks, etc.)						X				
8 UNEXPECTED LOADS	8.1 EARTHQUAKE	X	X	X					X		X
	8.2 GAS EXPLOSION, BOMB BLAST, EXPLOSIVE DUST	X	X	X					X		X
	8.3 COLLISION	X	X	X					X		X
	8.4 COLLAPSE OF ADJACENT BUILDINGS	X	X	X					X		X
	8.5 SHOCK LOADS (standing waves, tension forces in concrete)	X	X	X					X		X

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