REPAIR AND STRENGTHENING OF BUILDINGS

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ABSTRACT

Following a short introduction into the problems related with repair and strengthening of buildings including damage evaluation, design process, material selection and quality control, a review is given of the tests carried out at Karlsruhe. The aim and scope of these tests are explained and the parameters are discussed. Finally the test results are presented and some conclusions are drawn.

INTRODUCTION

The strategy we use should always be to try to strengthen buildings before they are damaged instead of waiting until we must repair them. Therefore a better title for my contribution would be "Strengthening and Repair of Buildings". This approach is especially useful in earthquake regions to help avoid human loss and structural damage.

After some general considèrations I will touch upon the materials used and explain what is typical for the different structural members to be strengthened or repaired. Last but not least I will present the results of tests carried out at Karlsruhe. I will try to keep my presentation short enough to finish in 20 minutes.

GENERAL CONSIDERATIONS

There are different reasons for strengthening and repair. There are an increasing number of old buildings, especially industrial buildings, which can no longer be used because of

the very low live loads which they were designed for. In order to avoid demolition and reconstruction, these buildings must be strengthened. Since the loads are static

and act vertically it is normally sufficient to double the load carrying capacity of the load bearing members, usually slabs and beams. The strengthening of columns is very often of less interest, as they are loaded indirectly. Strengthening of foundations should be avoided in this context.

Another field of interest is the hardening of special rooms, mainly in the cellars of residential buildings, for use as air raid shelters. They must resist shock loads with a static equivalent of about

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five times the original design live load. It is normally possible to sufficiently increase the load carrying capacity, but it is very difficult to ensure sufficient protection against heat and nuclear radiation.

The third field of interest concerns the improvement of earthquake resistance. Here we have both vertically and horizontally acting repeated loads. Very often buildings are heavily damaged during earthquakes and engineers must decide whether repair is possible. It is clear that it is not sufficient to reestablish the initial strength since the damage has demonstrated that the building was not properly designed and hence all attempts of recovery must be combined with substantial strengthening.

It is very important that all activities concerning strengthening and repair should be planned carefully. All participants in this process, including architects, engineers, contractors and craftsmen, are normally not very familiar with this type of business. Therefore drawings must be extraordinarily detailed and comprehensive. In certain cases they should be explained by added text, prescribing the essential steps of all important operations. Quality control is also essential and should be planned in detail.

MATERIALS

In this chapter only a short survey can be given of the materials often used in strengthening and repair.

Conventional concrete, cast--in--situ, is often used but sometimes with very unsatisfactory results. This concrete has annoying volume changes due to shrinkage, causing poor bond between the old and new concrete. A minimum water cement ratio is proposed. Placement techniques are very important. It must be insured that the concrete can be cast with good contact to all old surfaces and that it can be compacted sufficiently in its total volume. The old surfaces must be roughened and cleaned properly. Adequate curing is important to prevent rapid drying.

Shrinkage compensated concrete is produced using expansive cement or expansive admixtures (e.g. iron or aluminium powder). The intention is to obtain an appreciable volume increase to compensate shrinkage. All properties must be precisely known or extensive laboratory test should be made to determine all relevant properties. One of these properties is the interaction with the materials on the existing (old) surfaces.

Polymer modified concrete is more workable, has a lower shrinkage rate and a lower water--cement ratio than conventional concrete. These properties can improve bond between the old and new concrete. The polymers are normally supplied as a dispersion in water. They reduce (but do not eliminate) the need for curing. They can increase strength and chemical resistance. However polymer modified concretes should only be used after a thorough investigation of all relevant properties, especially compatibility with the existing materials.

In resin concretes the cement is replaced by a two component chemical system, consisting of liquid resin (epoxy, polyester, polyurethane, acryl etc.) and hardener. Resin concretes have some undesirable properties. Since they are very expensive they are usually only useful for patching small spalled areas of concrete and they have poor temperature resistance. Resin concretes cannot be placed during cold or very warm weather and on humid surfaces. They have a lower elasticity (Young's modulus), higher strength and better bond than conventional concrete.

Shotcrete needs special equipment and trained workmanship. It is often used for repair and especially for strengthening because of its numerous advantages. Shotcrete can be sprayed on vertical, inclined and overhead surfaces with a minimum of formwork. Its strength characteristics are high due to a low water cement ratio and to high compaction energy. Good bond can only be obtained between new shotcrete and old concrete or masonary on properly prepared surfaces that have been cleaned and roughened so that no loose aggregates present.

Shotcrete with fibres added has improved strength characteristics especially under tensile and impact loads. The fibres can replace parts of the reinforcement and increase the plastic deformability.

Grouts and resins are successfully used to fill cracks by injection. Grouts should be non--shrinking and the resins must have an adequate pot life. Their desired properties, including viscosity have to be precisely defined in order to select the correct formulation for the mixture. The injection pressure must be limited to an appropriate value in order to prevent additional damage caused by repair.

Grouts and resins are also used to glue steel plates. Their viscosity should be significantly higher than for injection. Additionally all other properties should be defined appropriately. A very severe problem may arise from the fact that all resins change their properties at temperatures higher than 100 °C. The strengthening carried out with resins is not fire resistant without providing additional protection.

STRUCTURAL MEMBERS UNDER CONSIDERATION

In the structural systems of our buildings typical members appear repeatedly. The difficult task of strengthening or repairing a structure can therefore be reduced to the general task of strengthening or repairing these typical members. We will now step through the most relevant ones and discuss concisely the most important questions to be considered.

Walls, especially shear walls, are very often essential parts of the load carrying system in particular for horizontal forces. They are typically loaded by shear forces acting in their plane. They can be strengthened by applying conventional concrete or shotcrete on one or two sides to increase their effective thickness. The two--sided solution generally results in better behaviour, but is more expensive and requires access to both sides of the wall. All unsymmetrical solutions produce high bond stresses and therefore need good doweling between the old and new parts. Appropriate solutions may be the application of epoxied bars with 90 °C hooks, welded ties between new and old web reinforcement (concrete cover must be chipped away), concrete dowels in drilled holes of greater diameter etc. Special consideration is needed to provide good transmission of forces between shear walls in different storeys or between shear walls and floor slabs.

Slabs of floor structures primarily have to carry the vertical live and dead loads. They can be strengthened by applying shotcrete with tension reinforcememt or steelplates on their lower sides to increase their effective thickness. This requires that substantial bond stresses must be safely transmitted between the new and old parts. A very severe problem are the shear stresses near the plates edges because the strengthening parts must end in front of the bearings. To optimize the existing solutions and to minimize the amount of material, time and cost was included in our laboratory test, which I will treat later.

Beams normally have to carry vertical live and dead loads transmitted by the slabs (in most cases they are not loaded directly) or they form part of a space frame carrying horizontal loads. They can be strengthened by jacketing with reinforced concrete or shotcrete on one, two, three or four sides, that is the lower side, the two side faces of the web, the combination of both and all four sides. In most cases the last solution is not possible, because concrete on the upper side conflicts with the regular usage of the building. Hence only unsymmetrical solutions with high bond stresses are realized. The scientific literature dealing with strengthening and repair shows that most researchers try to overcome this problem in different ways. One of our considerations was to avoid rather than overcome the bond problem and evaluate it by tests as I shall explain later.

Columns can be strengthed by jacketing with cast in situ concrete, shotcrete, steel profiles or by complete steel encasement. As the forces must be transmitted from the old to new parts bond is also the governing problem. Complicated and expensive solutions are often proposed to carry the loads from one storey to the next. Our tests showed that there may be simpler and cheaper ways.

It is not sufficient to consider only the different members of the structural system. The forces must be safely transmitted from one member to the next through each storey right down to the foundations. This requires all parts along the load path to be strengthened in an appropriate manner. **The beam--column--joints** of moment resisting frames are normally very critical regions. Using concrete jacketing or reinforcement with steel plates is applicable in this case. Great problems normally arise from the fact that access is restrained by the floor slabs.

The capacity of an existing structure, especially for lateral forces, may be increased by adding new structural elements. These **additional members** are most appropriate to enhance earthquake resistance. The choice of their type, number and size depends on the particularities of the existing structure and the functional layout of the building in question. These members can be:

Shear walls in a frame or skeleton structure
Additional shear walls in a shear wall structure
Additional frames in a frame or skeleton structure
Bracing (steel or reinforced concrete) in a frame or skeleton structure

In every case, the new structure, consisting of the old structure and the additional members, has to be analysed and designed. If there are any doubts about the quality of the old structural parts, the lateral forces should be carried by the new elements alone. Otherwise the lateral forces should be shared jointly by the old structure and the new elements depending on their stiffness.

Incorporating new structural components will change the dynamic behaviour of the structure considerably. The increase in stiffness will also tend to increase the seismic design forces. It also causes considerable redistribution of the forces between the lateral resisting elements.

Therefore it is very important to create most favorable conditions, as follows:

Avoiding a large concentration of forces in members with small strength and ductility capacities by locating the strengthening elements uniformly throughout the structure.

Improving the distribution of lateral force by reducing the effects of torsion and irregularities.

Providing sufficient strength, stiffness and ductility of the individual elements and of the whole structure.

Providing adequate strength in connections between the existing structure and the newly added elements.

Providing stiffness compatibility between the existing structure and the newly added elements.

In this context the very effective method of using upgraded non--structural partition walls as additional shear walls should be mentioned. Of course all the above mentioned restrictions, principles and constructive details should be considered in design.

EXPERIMENTAL WORK CARRIED OUT AT KARLSRUHE

Fig. 1 gives a survey of all tests on the subject carried out at Karlsruhe over some years. A total of 32 specimens were examined. This is a considerable number keeping in mind that one test costs several thousand dollars. Since a very wide range of questions was to be clarified, hardly more than one test was made for any one combination of parameters. That points out the preliminary character of the tests and the fact that, according to our intension and regarding the zeroes in the matrix, the tests will go on.

Walls were not tested at Karlsruhe. Therefore I will immediately proceed to the slabs. We started with statically loaded reinforced concrete slabs strengthed by steel plates glued with epoxy. Specimen V0 to V4 had inclined end anchors (fig. 2). The end anchors should strengthen and reinforce the critical region directly behind the steel plate's end, where the combination of high bending and shear stresses caused failure in some of the reinforced concrete slabs. Slab V5 was additionally supplied with undercutting anchors (fig. 3). These are anchors with conical holes. With the specimen PLV3 to PLV6 thicker steel plates and more anchors were used (fig. 4). The static tests clearly showed that it is possible with the proposed method to increase the load carrying capacity by a factor of about 6 or 7. But in all cases a sudden failure with low ductility was observed. Under shock load premature bond failure in the epoxy glue occured (fig. 5). Therefore we tested the behaviour of four slabs (PLV3 to PLV6) completely without resin, where the bond forces between steel plates and concrete were only transmitted by anchors alone. This test clearly showed that the defined aim (strengthening factor of 6 or 7) could be obviously reached by this simplified and often used technology which can be applied by skilled workers without special training. Whilst the load carrying capacity was comparable, the stiffness was significantly lower. This gives higher ductility and is therefore not a disadvantage for shock loading. The sudden failure could definitely be prevented.

A total of 12 **beams** were tested. We used T--beams in order to simulate the influence of the floor slab. The beams were jacketed on three sides of their webs with shotcrete containing reinforcement or fibres. The stirrups were welded at their upper ends onto steel profiles anchored in the old concrete (fig. 6). The longitudinal bars were connected in a similar manner with the old concrete. The aim was to double the load carrying capacity. The results clearly showed that the limiting parameter is bond, which cannot be predicted with sufficient accuracy. Therefore the last two specimens were tested with the bond completely eliminated. As you can see in fig. 7, it was possible to reach this goal, but it was necessary to provide well designed and well anchored longitudinal and stirrup reinforcement of sufficient size in the strengthening shotcrete shell. An additional test showed that fibres could replace stirrups but not bond. Therefore this result is of no relevance.

Last but not least let me present the results of the column tests. We tested a total of 8 columns with concentrically applied static loads. We also tested columns with tranverse shock loads but since strengthening or repair was not considered therefore they will not be mentioned. The test setup can be seen in fig. 8. All columns were jacketed on four sides with reinforced shotcrete. They were pretensioned by a concentric steel rod before jacketing, in order to simulate dead load. The goal was to verify that the concrete core of the old column was able to carry the doubled load after strengthening with closely spaced stirrups. Fig. 9 shows the instrumentation. In most tests, the outer concrete shell was not loaded at the columns ends in order to simulate the influence of shrinking. The test forces were only applied on the old core of the concrete (fig. 10). The problem was to transmit an appropriate part of the load to the outer concrete shell by bond. The results clearly showed that this aim could be reached if a sufficient number of well designed stirrups were supplied. Remarkable damage could only be observed in the bond transmitting regions (fig. 11) and could be limited by confining stirrups activating a three dimensional stress state in the concrete core. In addition, three of the specimens had two artificial cracks (fig. 12) near the center of the length to simulate the influence of cracks caused by shrinkage. The test results of these columns were nearly the same. Fig. 13 shows all test results, where you can also see the sufficient capacity of the specimen with artificial cracks.

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Tested Specimen

	Walls	Slabs	Beams	Columns	Beam-Column-Joints
Static Load	0	7	10	8	0
Shock Load	0	5	2	0	0
Repeated Load	0	0	0	0	0
Total	0	12	12	8	0
Sum of All Specimen					32

Fig. 1

Slab V4

Slab V5

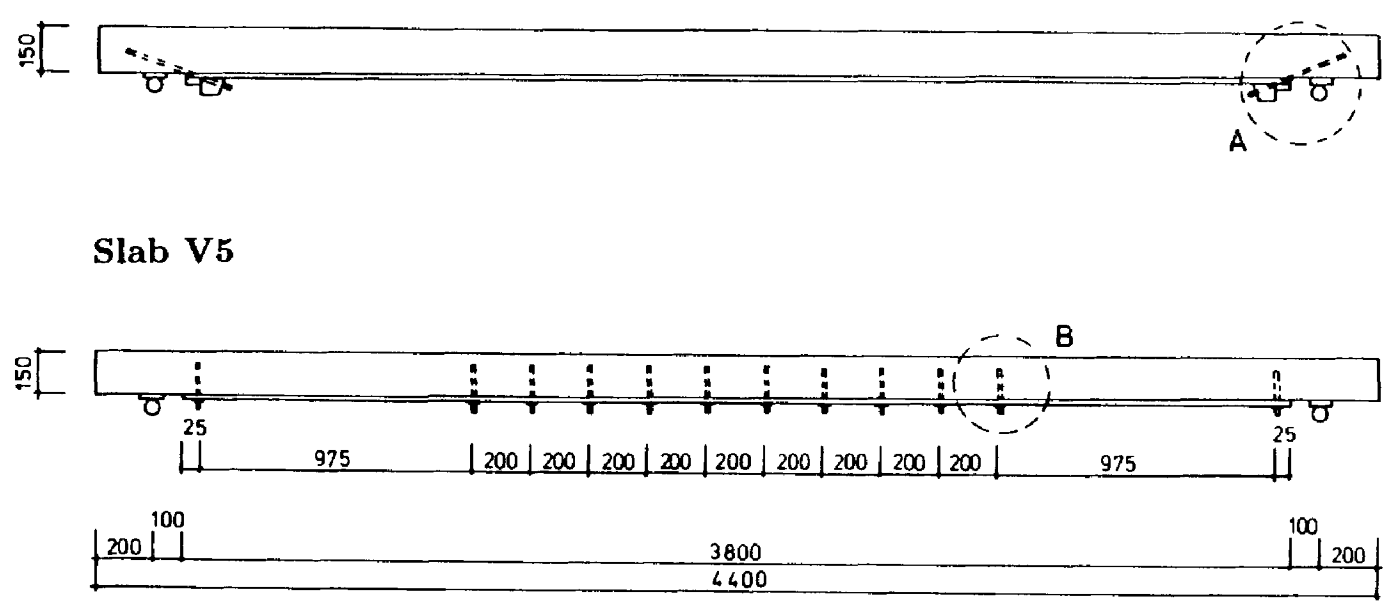
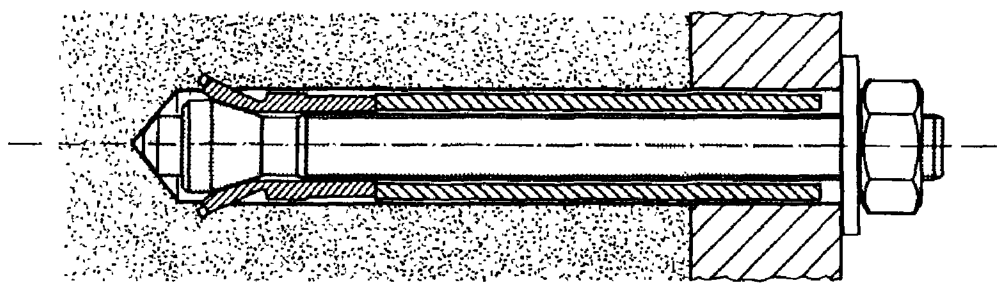


Fig. 2



Undercutting anchor (UPAT)

Fig. 3

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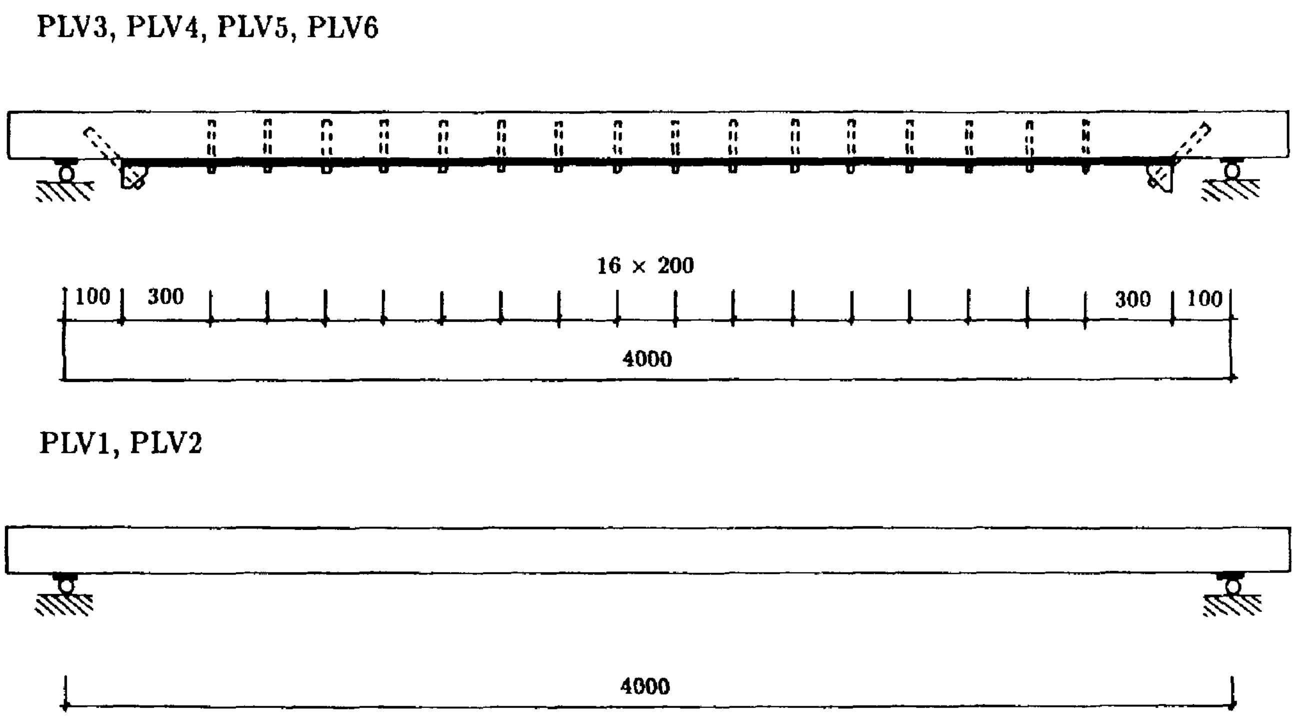

Fig. 4

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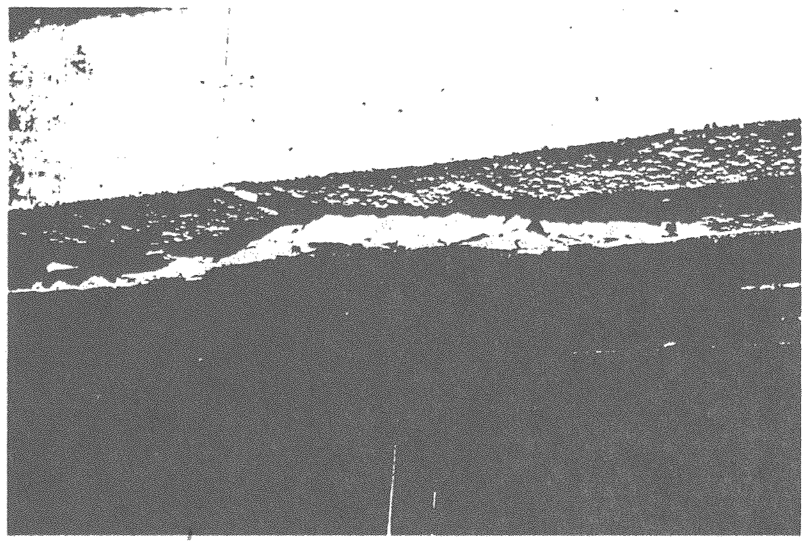

Fig. 5