

Design of structural repair schemes for RC structures

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ABSTRACT: The most pertinent issues to be addressed by the engineer in preparing the strategy for repair of damaged reinforced concrete buildings are discussed. This paper aims to emphasise the need for redesign and focuses on matters such as capacity over-strength in existing members, level of uncertainty in determining loads and structural over-strength due to simplifications in analysis. Considerable savings in repairs can be achieved by accurate diagnosis of errors and capacity reserves, use of non-linear analysis and selective repair of reinforced concrete structural members.

1 INTRODUCTION

The design process is considered to have finished at the end of construction of the building structure and it often is finished before the foundations are laid. Structural damage (resulting from combinations of design and construction errors, change of the buildings function, accidental loading and loading due to natural disasters) is very often not identified as such, and cosmetic repairs are undertaken to conceal the obvious defects.

The strategy for repair should necessarily involve the actual redesign of the structure so as to achieve an acceptable level of safety as shown in figure 1 and outlined below:

1 Accurate assessment of 'as built' capacity

A prerequisite for any structural intervention is an accurate assessment not only of the damage levels but also of the actual potential of the structure as built. The design capacities are necessarily conservative and therefore as built capacity should be estimated and used in the analysis stage of the repair process.

2 Re-estimation of loading

The design loads are often unknown during the design stages and allowance is made for finishes and live loads for different circumstances. Improved knowledge of the exact level of loading, at which the structure is being subjected to, can lead to a more precise determination of the forces applied to the critical members.

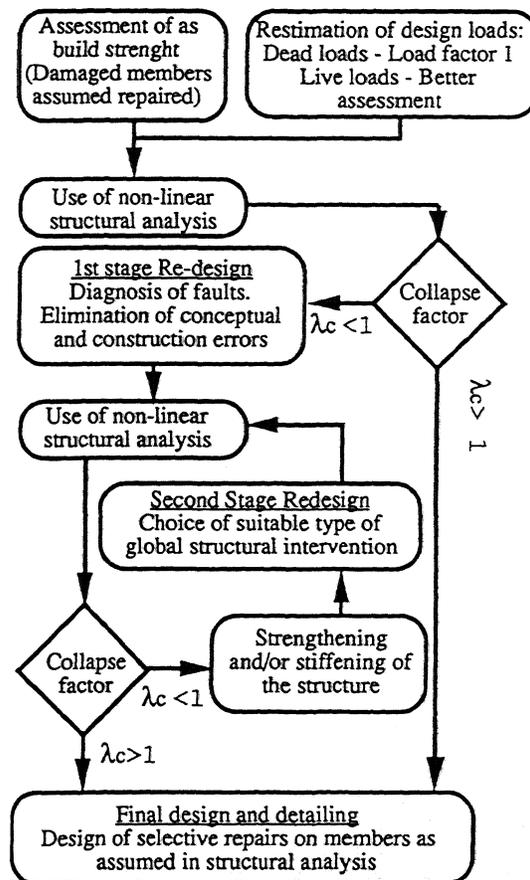


Figure 1 Flow chart for design of RC repairs

- 3 *Use of improved analysis techniques*
Elastic analysis is used almost exclusively for the solution of the structural problem. Nonetheless, design of members is most often undertaken by ultimate capacity or plastic methods. Local redistribution due to the expected plasticity is allowed by some codes of practice, but the overall enhancement of the capacity of structures due to plasticity has not yet been appreciated nor utilised.
- 4 *Elimination of errors*
Weak links in a chain always fail first, and hence, the elimination of inherent conceptual and construction errors that constitute a weak link is essential.
- 5 *Prudent choice of structural intervention*
Strength and deformation demand on members resulting from reliable structural analysis will identify the level of strengthening that is required by the structure. Both strength and ductility enhancement might be necessary with the addition of new members or the strengthening of existing ones.
- 6 *Selective repair techniques*
Targeting the defective and inadequate members is essential in order to upgrade their capacity to the correct level and not higher, as is often the case in non-selective schemes.

In this paper the various stages involved in redesign are discussed and recommendations are made for the achievement of the most economic and safe result.

2 RECALCULATION OF 'AS BUILT' CAPACITY AND EXPECTED ACTIONS

The safety margins of the structure and individual members are a function of the 'as built' capacities and of the present and expected loading for the actual building.

2.1 'As built' capacity

During the design process the variability of material strength due to the manufacturing and construction processes has to be accounted for in a conservative manner. Hence, the calculated design capacities, C_d , are much less than the actual ones, C_a , for undamaged members, and a totally new estimate of residual capacity, C_r , is required for damaged members.

In design, the characteristic rather than the actual (average) concrete compressive strength is factored by a factor of 1.5 whilst the tensile strength is ignored for flexure calculations. Additionally, the concrete

strength increases with time, and for most completed structures the long term strength is available. Higher concrete strength and ductility are also available in well confined areas of critical members.

Steel characteristics are considered to be less variable and, hence, a lower safety factor of 1.15 is used. Nonetheless, the actual (average) steel yield strength can be significantly higher than the characteristic strength by more than 10% in several cases. Moreover, the ultimate capacity is even higher by a further 20% due to strain hardening and areas of steel reinforcement provided during design are higher than required [1].

Consequently, by measuring the correct dimensions, location of reinforcement and strength of materials, it can be established that undamaged members possess higher capacities, C_a , than designed. The value of C_a could be as much as 100% higher than C_d , as demonstrated above, but on the average a 30% to 60% higher value than C_d is expected. The stiffness of members varies with time as well as with the level of actual strength of materials and previous loading history. For critical members a reduced value for stiffness may be more suitable for use in analysis, since it enables better redistribution of forces.

Damaged members need special attention and assessment of residual stiffness and strength C_r is more difficult to make. For severely damaged members, it is pointless to use C_r for analytical purposes and the design capacity, C_d , can be initially utilised to establish the level of forces in the structure. In order to account for this a minimum level of structural intervention can be assumed to restore the initial capacity of damaged members, as shown in figure 1.

2.2 Expected actions

Even though damage in a structure implies that the imposed actions were higher than the design ones, this cannot be true for all design actions at all locations. In an existing structure, the uncertainty of the level of the total expected loading, Q_{at} , is somewhat reduced by making improved estimates of the existing permanent loads, Q_{ap} , and better assessment of the type and likely distribution of live loads, Q_{al} . In general ' Q_{ap} ' will be lower than the design permanent loads, Q_{dp} , which are obtained by multiplying the expected loads by a factor of 1.4. Most ' Q_{al} ' will also be lower, since a better definition of the use of the different spaces can be made,

but new loads due to change of use or changes in design codes will have to be accommodated. In particular, increased levels of seismic loading might be required to be resisted for risk mitigation.

By using the capacity and action ratios (provided $C_d > Q_{dt}$) the safety levels of existing structures can be assessed, as shown in figure 2. By accepting the principle that a uniform safety level is desired for all critical structural members, any reserve in member capacity can be utilised to offset increased loading demand. Safety level is calculated as shown in equation 1 below:

$$\text{Safety Level SF} = \frac{\text{Capacity Ratio}}{\text{Action Ratio}} = \frac{C_a Q_{dt}}{C_d Q_{at}} \quad (1)$$

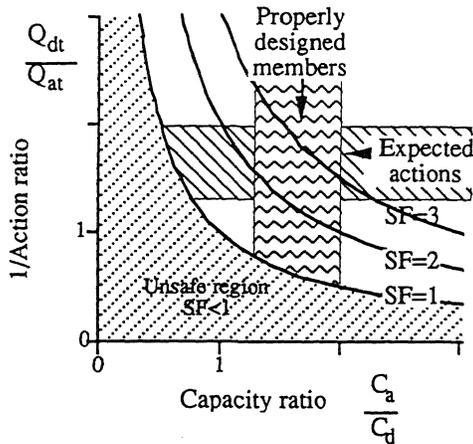


Figure 2 Safety levels in existing structures

3 ANALYSIS TECHNIQUES

Re-analysis of the existing structure is necessary both as a means of determining the causes of failure as well as identifying the critical elements when the newly determined expected loading is established. Elastic analysis is used almost exclusively for analysis of RC structures. However, provided brittle failures are avoided by suitable strengthening of culpable members, elasto-plastic analysis techniques could be used leading to significant reductions in the calculated applied actions. Additional sources of inaccuracies in the analysis arise from the stiffness and boundary conditions used.

3.1 Boundary conditions

The foundation conditions can be better assessed in a completed structure and a better estimate of the stiffness provided by the ground can be used in the analysis.

Differential settlement effects, proximity to adjacent structures and the possibility of pounding should be taken into consideration in the re-analysis.

3.2 Stiffness

In highly statically indeterminate structures, such as RC frames, the relative stiffness of members governs the distribution of forces. Consequently, the correct estimation of forces requires the precise determination of the member stiffness, which is very much influenced by the material characteristics, the loading history and the state of longitudinal stress. Current elastic methods are usually unable to modify the stiffness of elements according to their axial state of stress.

3.3 RC Plasticity

Plastic deformations in RC members whose yield capacity is exceeded can help to redistribute forces, thus mobilising a larger number of elements more effectively. The plastic capacity of RC sections is higher than their yield capacity by 15-50% depending mostly on the steel type used and steel distribution. The use of this "plastic reserve" strength and of the redistribution effects, due to non-linearities, means that the structural plastic capacity can be several times higher than the elastic design capacity. This is especially important when re-analysing structures with increased loading requirements, since significant savings in the subsequent redesign can be achieved. Care should be taken to ensure that high rotational capacity, which is necessary for plasticity to propagate, is available in all relevant members. The actual rotational capacity of members is underestimated by current design codes, especially when they contain low percentages of reinforcement [2].

Improved predictive techniques for estimating rotational capacity as well as the determination of the full moment rotation characteristics of RC members under various combinations of loading should be the subject of further research. Additionally, the use of simple non-linear analysis for RC structures should replace the currently used elastic analysis.

4 STRUCTURAL INTERVENTION

4.1 Elimination of inherent errors

The first stage in restoring the structural ability to resist the expected forces, is to ensure that any conceptual and construction

errors are rectified. This process may involve correcting abrupt changes in stiffness, eccentricities in plan between stiffness and mass, as well as eliminating poor detailing, use of inferior materials etc. The elimination of such errors does not necessarily precede any further interventions, but is assumed to take place so that a preliminary analysis can identify the critical members and extent of structural deficiency, as shown in figure 1.

4.2 Extent of repair

Following a preliminary elastic analysis with reduced member stiffness, it is possible to locate all the critical members. Critical members are those members with a safety level SF less than 1, as shown in figure 2. Depending on the extent of the deficiency, necessary action needs to be taken.

Provided that the value of ' Q_{dt}/Q_{at} ' for the deficient members is higher than 0.5, then it might be possible to rectify the situation by utilising their plastic reserve. Simple moment redistribution can be undertaken to evaluate whether there is sufficient capacity reserve in non-critical members to resist extra moments and loads. A consequence of action redistribution might be the significant increase of the number of critical members. The development of localised or global plastic mechanism indicates that strengthening of some members will be necessary. The results of this exercise can be re-examined by non-linear elasto-plastic analysis.

All members identified as critical will be required to have sufficient rotational capacity so as to allow redistribution to take place. Enhanced rotational capacity can be achieved by providing confinement to the concrete in highly stressed areas. There are several means by which this can be achieved, but the authors are currently investigating several techniques by which external confinement can be applied without significant increase of the cross-section.

Strengthening of the structure is absolutely necessary, if the plastic potential of the structure following the initial elimination of errors is exceeded. Several techniques are used in practice, such as infilling selected bays with RC panels or braces, increasing the size of critical members either by extending or jacketing them, and adding new structural elements[3].

In properly designed strengthening, the overall deformations can be better controlled, but a serious disadvantage of strengthening in earthquake resistant design is the significant

increase of the imposed forces. This is especially serious at the foundation level, where extensive strengthening may be required. High cost and interference with the functionality of the structure can discourage owners from authorising essential repairs and opt for cheaper cosmetic patching up.

4.3 Selective repair

The design of repairs should take into account the assumptions made during structural analysis. Enhancement of strength would normally result in the enhancement of stiffness of the same member, and hence, higher forces would be attracted than for an assumed lower stiffness. Similarly, ductility enhancement in certain locations reduces the rotational stiffness and this may influence the ductility demand in other locations. Selective types of repair should aim to achieve only the enhancement in the desired quantity without interfering with other quantities.

5 CONCLUSIONS

- 1 Reinforced concrete members on the average have a higher actual capacity than assumed in design, by more than 50 %, due to the higher strength of materials and simplifications in design.
- 2 The lower uncertainty in determining the design loading for existing structures can permit the use of lower safety factors with consequent reductions in the levels of redesign loading.
- 3 Non-linear analysis of RC structures can result in significant savings due to the mobilisation of the "plastic reserve" and redistribution of forces.
- 4 Structural repairs should be designed in accordance with the assumptions made in the structural analysis. Selective repair of members is therefore essential if over-strengthening is to be avoided.

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