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Effect of member characteristics on the response of RC structures

A.S. Elnashai
Imperial College, London, UK

ABSTRACT: Seismic Design using the 'capacity' approach requires a high degree of control on the response and failure mode of RC structures. To advance the design process, individual response parameters, such as stiffness and strength in shear and flexure, as well as ductility, should be appropriately assessed and controlled. In this paper, assessment of individual components of deformation in RC structures is discussed and problems encountered in interpreting test data are identified. Furthermore, techniques that lead to the modification of one response parameter without affecting the others are proposed, hence enabling control of the behaviour. Several practical re-design, assessment and intervention scenarios are presented, to confirm the need for the proposed selective assessment and intervention approach.

1 PREAMBLE

The behaviour of RC structural members may be characterised, in general, by a 'flexural' and a 'shear' component. Moreover, the response parameters of each component can be described in terms of stiffness and strength, in addition to overall ductility, as shown in the Table 1. below. Such a classification is of significance, not only for the understanding of structural response, but also for re-assessment of existing structures and devising effective repair and retrofitting strategies.

The above argument has implications on future investigations of structural behaviour of RC members subjected to earthquake loading. From the structural response investigation standpoint, methods of assessment, such as experimental testing, have to make a clear distinction between the response in flexure and that in shear. There are several examples of research efforts that have recognised the significance of separating flexural and shear deformation contributions (Lefas, 1988, Lefas and Kotsovos, 1987), but had shortcomings with regard to (i) application of realistic boundary conditions, and to (ii) use of accurate methods for separating the two deformational components. Both issues; boundary conditions and shear/flexure separation methods, where studied by Pilakoutas (1990) and Elnashai and Pilakoutas (1991), as discussed below.

Another aspect of seismic response of RC structures which is affected by the concept of individual member response characteristics is re-assessment of existing buildings, where newly-defined regularity criteria of stiffness and strength are imposed on a non-conforming structure. This imposition of new limits of acceptability dictate a re-assessment based on separate consideration of stiffness, strength as well as ductility.

Table 1. Response Characteristics of RC Members.

	K_f	K_s	C_f	C_s	μ_d
Re-instatement	✔	✔	✔	✔	✔
Enhancement	✔	✔	✔	✔	✔
Reduction	×	×	✔	×	×

K_f Flexural stiffness
K_s Shear stiffness
C_f Flexural capacity
C_s Shear capacity
μ_d Ductility ratio
✔ May be required
× Not normally required

Finally, the repair and retrofitting process of damaged RC structures should be directed towards not only repair of the individual member, but also the effect of this repair on the overall structural response.

In the light of modern code development, [where the evaluation of a 'behaviour factor' is central to the seismic design/assessment/repair process] the above three aspects of response characterization require techniques to test, design and repair structural systems, bearing in mind the individual response parameter of the members. The modification of these parameters; stiffness; strength; ductility, would ideally lead to a higher behaviour factor. In most cases covered by Table 1 above, it is essential to assess and affect (for design and repair, respectively) the member response parameter under consideration, with little or no effect on other parameters; selective assessment/intervention, hereafter referred to as 'SAI'. Adoption of this approach is in harmony with the capacity design philosophy. It enables tight control of the behaviour and failure mode of RC structures, leading to rational design, assessment and repair solutions, as discussed below.

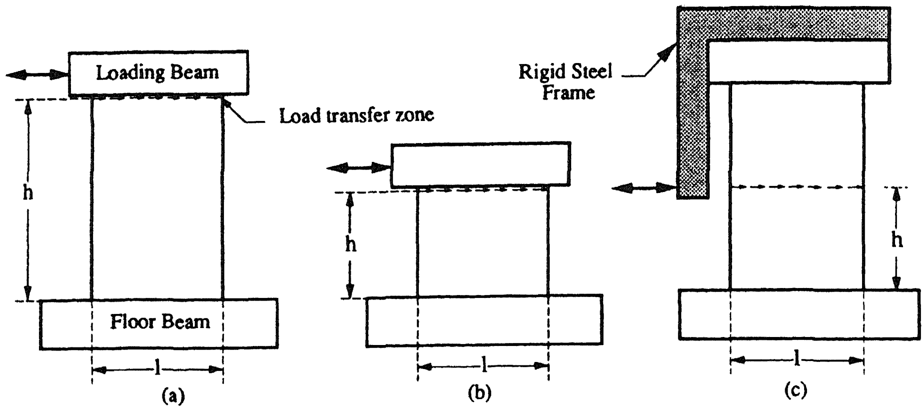


Figure 1. Test Arrangements (a) Flexure, h/l ≥ 2.0 (Pilakoutas, 1990), (b) Shear, h/l ≤ 1.0 [loading beam applies unrealistic boundary conditions], (c) Shear, h/l ≤ 1.0, realistic boundary conditions (Lopes, 1991).

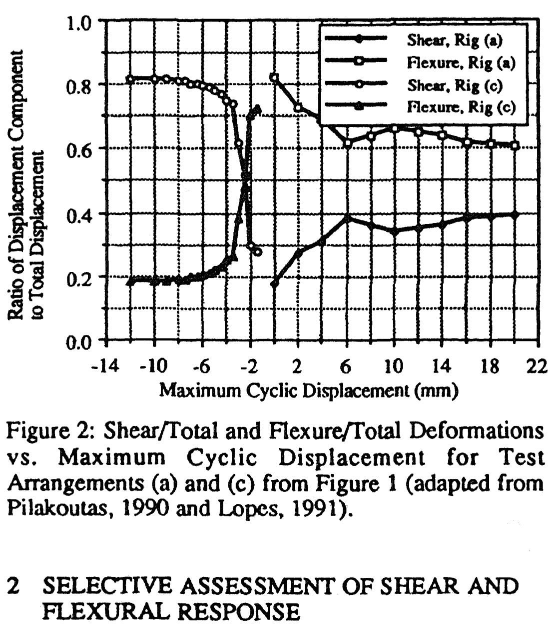


Figure 2: Shear/Total and Flexure/Total Deformations vs. Maximum Cyclic Displacement for Test Arrangements (a) and (c) from Figure 1 (adapted from Pilakoutas, 1990 and Lopes, 1991).

2 SELECTIVE ASSESSMENT OF SHEAR AND FLEXURAL RESPONSE

Reinforced concrete members respond in a mixed flexural/shear mode, dependent on their geometry, design, loading and boundary conditions. Whilst the behaviour of members such as shallow beams and beam-columns is mainly governed by flexure, RC walls respond in the above-mentioned mixed mode. Therefore, it is crucial that testing arrangements can reproduce both aspects of the behaviour, if the observations are to be suitable for development of design criteria. Two testing programmes were completed at Imperial College (Pilakoutas, 1990 and Lopes, 1991), where the flexural- and shear-dominated behaviour was investigated. As shown in Figure 1, the testing arrangement 'a' leads to testing of a geometric aspect ratio of about 2.0, which is the approximate limit between flexure and shear prominence. Testing arrangement 'b' is that used by several researchers to investigate the response of squat walls (Lefas, 1988). In the latter case, in addition to problems due to direct load-transfer from the loading beam to the foundation, the loading beam applies a confining stress condition which is not present in the bottom portion of RC walls in a building. Observations from such testing arrangement should be treated with caution. Rig 'c', on the other hand, applies the load through an arrangement that leads to a 'natural' transfer of load to a low aspect ratio wall, hence the results obtained will reflect the true behaviour.

Moreover, several methods may be used to separate shear and flexural deformational components (Pilakoutas, 1990) based on the number of transducers used along the height of the wall. The assumption of uniform or linear curvature distribution used by some researchers leads to erroneous results (under-estimating/over-estimating flexural deformations dependent on whether a linear or uniform curvature distribution along the height has been assumed, respectively). The method adopted by Pilakoutas (1990) leads to accurate estimates of the balance between shear and flexural deformations. The same technique was utilized by Lopes (1991) to process the data obtained from a series of tests with success. Typical curves depicting the ratio of shear and flexural deformation component to total deformation are shown in Figure 2.

In Figure 2, it is clear that the balance of flexure-to-shear displacement changes dramatically, favouring a shear-dominated mode, as the cyclic displacement amplitude increases. Moreover, it was observed during the tests conducted by the Earthquake Engineering Group at Imperial that this balance is most significantly affected by the loading history; monotonic, cyclic, number of cycles. It is therefore of utmost importance to treat observations from monotonic test and limited load-control cyclic tests with caution in seismic design applications.

The above discussion serves to highlight the central role played by stiffness and strength components;

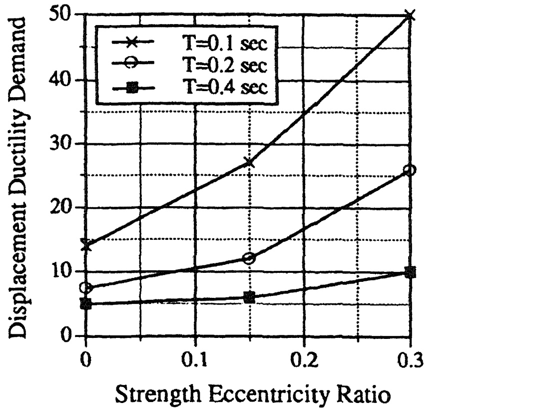
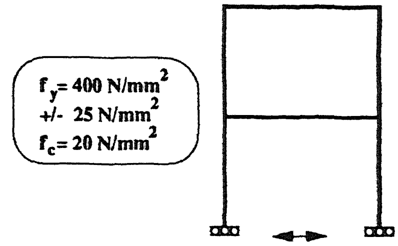


Figure 3. Effect of Strength Eccentricity on Displacement Ductility Demand under El Centro earthquake, for three periods of vibration of a three-element model (adapted from Xian, 1992).



	Displacement Ductility μ_d	Energy Absorption kNm	Behaviour Factor 'q'
Max.	10.11	73.05	5.50
Min.	6.57	24.89	3.75
%	153%	293%	146%

Figure 4. Response Parameters of RC Frame with Material Variability

separately and collectively, in the seismic response of RC structural members.

3 INDIVIDUAL MEMBER CHARACTERISTICS; SCENARIOS AND REQUIREMENTS

Above, a general statement is made regarding the necessity of developing techniques to assess and affect individual member characteristics; SAI. Below, some typical situations dictating the application of SAI techniques are presented.

3.1 *Strength-Only Scenarios*

3.1.1 *Capacity Re-design*

Within the context of the 'capacity design' concept, failure mode control is essential for the realisation of the predicted behaviour and sequence of plastic hinge formation. Such concept has recently been forwarded, hence existing structures would only fortuitously conform to a desirable failure mode. The first proposed scenario, in support of the case for SAI (selective assessment/intervention) is the re-assessment of a structure designed according to conventional 'direct design' concepts. It is required to alter the sequence of plastic hinge formation to satisfy the new 'capacity design' failure mode. However, the stiffness distribution in the structure is in accordance with the code procedure, hence no increase in stiffness is required. Indeed, an increase in stiffness would cause violation of the regularity conditions specified by the code. In this case SAI is required, to effect an increase in strength without an increase in stiffness.

3.1.2 *Strength Eccentricity*

Seismic design codes impose conditions to reduce the effect of torsional vibrations on the shear forces at column heads. This is defined in terms of limitations on the eccentricity, defined as the distance between the centre of mass (where the inertial load is applied) and the centre of rigidity (where the elastic reaction to the inertial forces is applied). However, no provisions exist for strength eccentricity. This effect was shown (Xian, 1992) to increase ductility demand, as the structure starts to respond in the inelastic domain; Figure 3.

It is conceivable that a structure may be stiffness-symmetric but strength-asymmetric. This can be demonstrated by considering the relationship between strength and stiffness of moment resisting frames and RC walls. The latter may be used to balance the frames stiffness distribution, thus almost certainly creating a strength eccentricity. This scenario leads to the conclusion that an SAI scheme is required to increase the strength of parts of the structure without a consequential increase in the stiffness.

3.1.3 *Variability in Materials*

The effect of variability in steel yield stress on seismic response and design has been studied for steel frames (Kuwamura and Kato, 1989, Elnashai and Chryssanthopoulos, 1990 and others). The effect of yield stress variations on the behaviour factors and energy absorption of RC frames was studied by Alexandrou (1991). For a mean steel yield of 400 N/mm^2 and a standard deviation of 25 N/mm^2, a frame (Figure 4) was analysed using the FE package ADAPTIC (Izzuddin and Elnashai, 1989).

The above analysis highlighted the effect of local member strength on the overall seismic performance; the frames for which the results vary by up to 293% are nominally identical. It is hence concluded that in such cases, a strength-only intervention would be required, and no stiffness change should be allowed, thus emphasising the importance of the concept of selective assessment/intervention.

3.2 *Stiffness-Only Scenarios*

There are several applications where an increase in stiffness without an increase in strength would be required. The most common of such scenarios is the case of damage to a reinforced concrete structure due to small magnitude earthquakes, which will reduce the stiffness of the structure due to cracking. However, for flexural members in particular, a commensurate reduction in strength does not necessarily occur. Therefore, in repair of such a structure, reinstatement of stiffness, with no effect on strength, should be the objective of the intervention scheme.

The second scenario of stiffness-only intervention is the case of a stiffness-irregular structure that violates newly-imposed code design criteria. Application of a conventional intervention scheme, such as jacketing, which has a simultaneous effect on both stiffness and strength, would require a complete re-design to ensure that the ductility of the structure is unaffected. It follows that application of an SAI intervention, under stiffness-only conditions, is an appropriate solution, leading to the satisfaction of code requirements without a complete re-design.

3.3 *Ductility-Only Scenarios*

Here, inadequate detailing of the existing structure requires intervention to increase the ductility of the member, without significantly affecting its strength and stiffness. This is a commonly-encountered problem, and its solution is considerably more straightforward than the stiffness- or strength-only intervention, as discussed in subsequent sections of this paper.

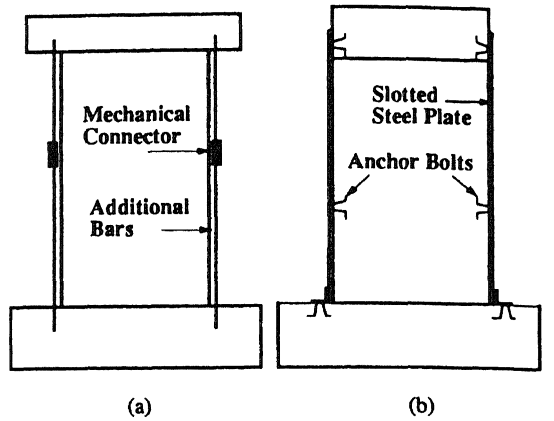


Figure 5. Strength-only Intervention (a) use of additional bars and mechanical couplers and (b) use of slotted steel plates and bolts.

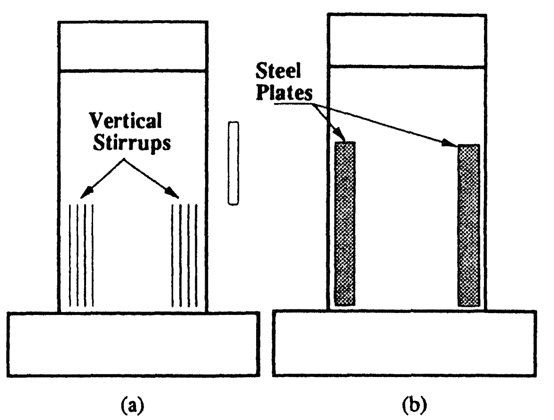


Figure 6. Stiffness-Only Intervention using (a) closed vertical hoops and (b) glued steel plates (both systems are not anchored to either of the two top and bottom slabs).

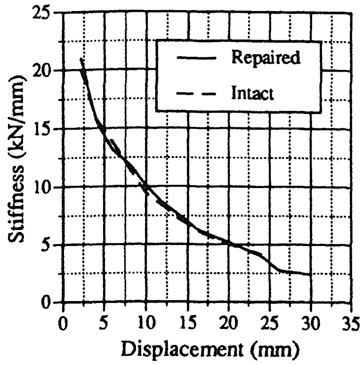
4 SELECTIVE INTERVENTION

In the above sections, the consequences of local member behaviour on the overall structure were exemplified by focussing attention on a number of cases where the global assessment and design criteria dictate the specific objective of the local intervention scheme. Here, some novel ideas aiming at selectively affecting a single response parameter with little or no effect on other structural characteristics are presented. Preliminary results from stiffness-only selective intervention are given.

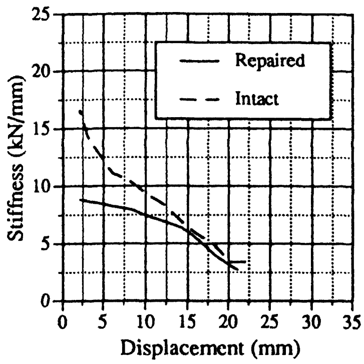
4.1 *Strength-only Intervention*

Two schemes were designed and tested at Imperial College, where additional steel bars or plates are used, in conjunction with a delay mechanism, to increase the strength without affecting the stiffness. In scheme (a), shown in Figure 5, steel bars are added and a mechanical coupler is used to adjust the tolerance in displacement beyond which the bars take part in the load-carrying process. In the second case (b), steel plates are bolted to the wall sides, where the bolts can travel within a groove before bearing on the steel plate, thus contributing to the flexural capacity of the member.

In a practical situation, several other alternatives exist, such as the insertion of steel bars within a plastic duct, with a bar length longer than the distance between the top and bottom slabs. The above schemes are indeed practical, since they are worst as cumbersome as existing jacketing techniques.

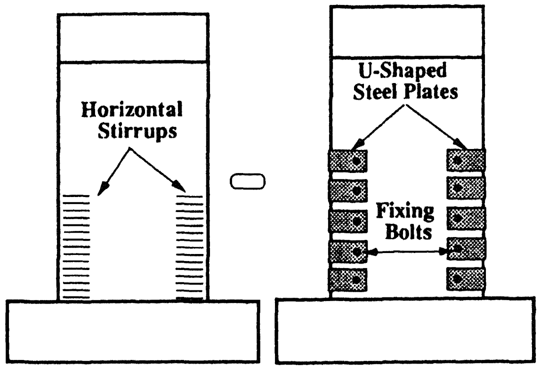


(a)



(b)

Figure 7. Stiffness before and after repair using (a) steel plate adhension and (b) epoxy injection.



(a) (b)

Figure 8.Ductility-Only Intervention using (a) closed hoops and (b) glued U-shaped steel profiles.

4.2 *Stiffness-Only Intervention*

According to the sample scenarios given above, the situation may arise where an increase in stiffness without and increase in strength is required. This can be effected by one of the two techniques shown in Figure 6 below, amongst others.

The scheme in Figure 6 (a) comprises the addition of closed hoops in the vertical plane spanning the heavily cracked zone (flexural plastic hinge). The hoops are not attached to the foundation beam, hence they do not contribute to the strength of the critical section. The number and location of the vertical hoops dictates the level of stiffness increase.

In the second proposed scheme, shown in Figure 6 (b), a steel plate is glued to the area affected by flexural cracks, using epoxy mortars. This plate is again attached to neither the loading nor to the foundation beams, hence provides no continuous load-transfer mechanism. The location and width of the steel plate dictates the level of stiffness increase imposed on the RC member, hence control over the response parameter can be exercised. Preliminary results from tests at Imperial College (Elnashai and Salama, 1992) indicate that this technique is more effective in stiffness re-instatement than epoxy resin injection; Figure 7. Moreover, it is not possible to control accurately the extent of epoxy mortar penetration, hence little or no control can be exercised on the level of stiffness increase.

In Figure 7 (a), the stiffness is plotted vs. maximum cyclic displacement for a reinforced concrete wall in the intact and repaired (by steel plate adhesion) states. Figure 7 (b) shows the stiffness of a wall repaired by epoxy resin injection. It is demonstrated that the intact stiffness is reinstated by using the steel plate. Moreover, the strength of the wall in (a) was unaffected.

4.3 *Ductility-Only Intervention*

This is the simplest application of SAI, where the structural member is deemed satisfactory for both stiffness and strength criteria, but is required to demonstrate extra ductility in order to increase the global behaviour factor. Here, additional stirrups may be added by drilling through the member. Alternatively, steel U-shaped plates may be bolted to the area where additional ductility is required, as shown in Figure 8. In either situation, the number of bars (or plates), their diameter (or thickness) and their spacing dictates the level of ductility enhancement.

The application of such techniques will have no effect on the stiffness and strength of the member, since it is only affecting the confined compressive strength of the concrete. [It is established that the effect of concrete confinement on flexural strength is minimal, especially for low levels of axial load].

5 CONCLUSIONS

Advanced seismic design philosophies render full control on the behavioural pattern and failure mode of structural members and systems necessary. Therefore, individual contributing mechanisms should be identified and controlled. The former requirement; identification of individual load-resistance mechanisms, requires careful consideration in load application, history and boundary conditions used in the laboratory and in analysis, as well as accurate techniques to separate the two contributing mechanisms; shear and flexure. The importance of this identification is highlighted by consideration of the balance between shear and flexural displacement components from tests on RC walls; the ratio of shear-to-total and flexure-to-total displacements is shown to vary continuously with the increase in the maximum cyclic displacement and the number of cycles.

The requirement of control poses new challenges to the designer, whereby means of affecting one response characteristic without the others have to be developed. It is shown above that realistic design, repair and retrofitting scenarios lead to the conclusion that stiffness, strength and ductility should be treated selectively.

Methods of affecting individual response parameters are suggested, based on tests and analysis conducted at Imperial College, and preliminary results are given. It is demonstrated that this approach; selective assessment/intervention, is the answer to the above-mentioned identification and control requirements. The general approach used in this paper provides a framework within which tighter control on the seismic response of RC structures can be exercised.

6 ACKNOWLEDGEMENT

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