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A proper member model for member flexural behaviour at fixed-ends

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ABSTRACT: Key elements in seismic assessment of an existing reinforced concrete structure are the identification of the non-linear deformation sources of a member and adequate modelling of the identified non-linear behaviour. Tests on as-built reinforced concrete components with plain round longitudinal bars shows that the major non-linear deformation is due to flexural cracks of beams at beam-column interface, referred to as the fixed-end rotation of the beams. Beam deformation at the fixed-end occurs mainly due to severe bond degradation along the longitudinal reinforcement within the joint core and it is associated with beam force transfer across the joint core and therefore associated with the other members framing into the same joint. All the existing member models assume that post-elastic behaviour of a member is fully determined by the considered member. Hence, there is a need for incorporating other members at the same joint in adequately modelling member behaviour at the fixed-end. Subsequently, a tentative member model is proposed.

1 INTRODUCTION

A major earthquake imposes large displacements on structures and the resulting structural deformation is usually well beyond the elastic response range. Hence the key element in assessing the seismic performance of existing reinforced concrete structures during a major earthquake is the post-elastic seismic responses of the structures.

Tests and analyses frequently show that, with an analytical model capable of reproducing the inelastic response of individual reinforced concrete components with reasonable accuracy, the global post-elastic behavior of the whole structure can be adequately estimated by integrating the local behavior of individual structural components. Hence, the determination of the global non-linear behavior of the whole structure depends on the adequacy of the information on the local non-linear behavior of individual reinforced concrete components.

To model the post-elastic behavior of the individual reinforced concrete components, it is necessary to identify the regions where nonlinear deformations are expected, and also to find the strength attainment and maintenance of these identified regions as the non-linear deformations progress, as so-called hysteretic behavior.

Conventional theory assumes that the post-elastic flexural deformation of reinforced concrete members will be in the plastic hinge regions (PHs), which have a length varying from 0.5 to one unity member depth, and the shear resisting capacity in PHs provided by concrete can degrade as the deformation progresses, and this means that relatively dense transverse reinforcement is required in PHs to prevent the premature shear failure before the attainment of the member flexural ductility. However, tests on as-built reinforced concrete components shows that a significant contribution of the member post-elastic deformation is from the rotational deformation at the fixed-end rather than the deformation spreading over a certain length, and this is especially true when the longitudinal reinforcement is from plain round bars as for the pre-1960s construction in New Zealand. Hence, in assessing the global post-elastic performance of a reinforced concrete structure, it is important to adequately model the post-elastic behaviour at the fixed-ends of an as-built reinforced concrete member.

This paper addresses the need for developing a new member model capable of capturing the observed evidence. At first, it discusses the fundamental differences of the observed deformation characteristics for plain round longituidnal bar case from the ordinary case. Then, a tentative member model is proposed for representing the post-elastic behaviour at the member's fixed-end.

2 TEST EVIDENCE

2.1 General

In a research program "Seismic assessment and retrofit of pre-1970s reinforced concrete building structures" conducted at the University of Canterbury, simulated seismic loading tests were conducted on as-built full-scale interior and exterior beam-column joint subassemblages reinforced by plain round longitudinal reinforcement (Liu et al 2002). Figure 1 shows the as-built test units EJ2 and EJ4. The two units are identical, and tested with different column axial load.

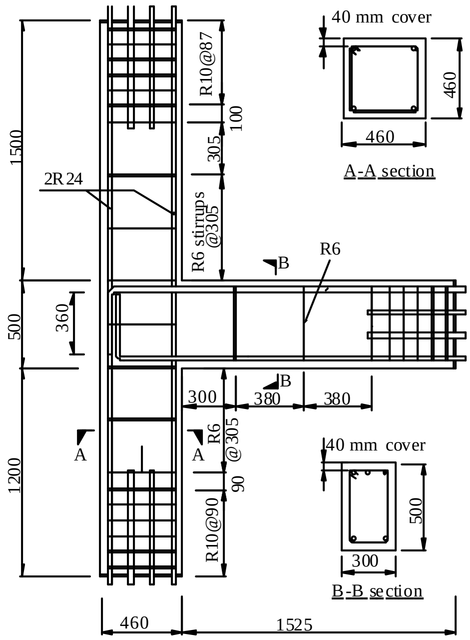
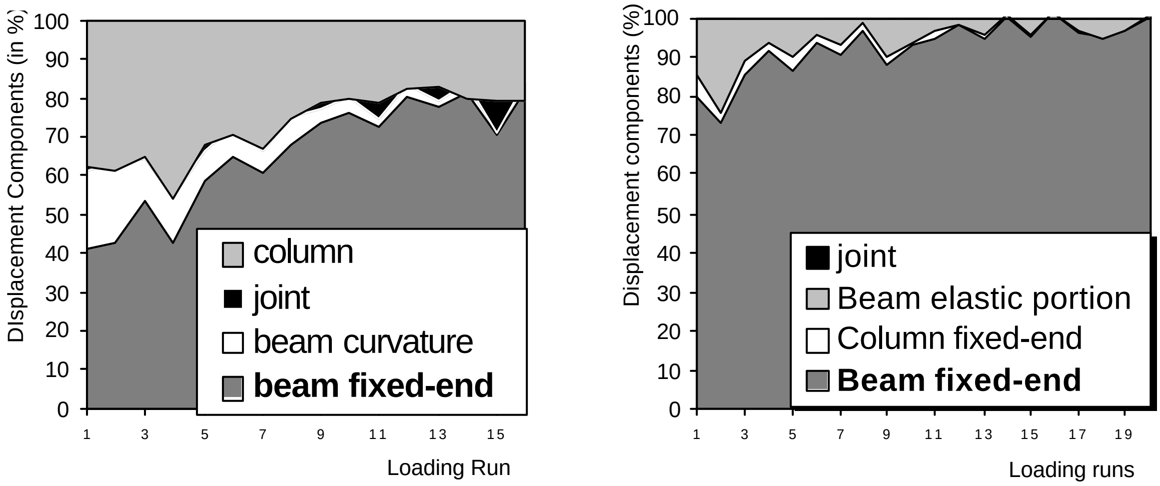


Figure 1. As-built exterior beam-column joint subassemblage reinforced by plain round longitudinal reinforcement

Figure 2 shows the displacement components measured for the as-built exterior beam-column joint subasemblage as a whole. Apparently, the total deformation of each subassemblage is mainly attributed to the beam deformation, and the contribution due to the shear distortion within the joint is very insignificant. Therefore, it is very important to adequately model the deformation and strength capacity of the beams in this case and the joint can be simply treated as rigid.

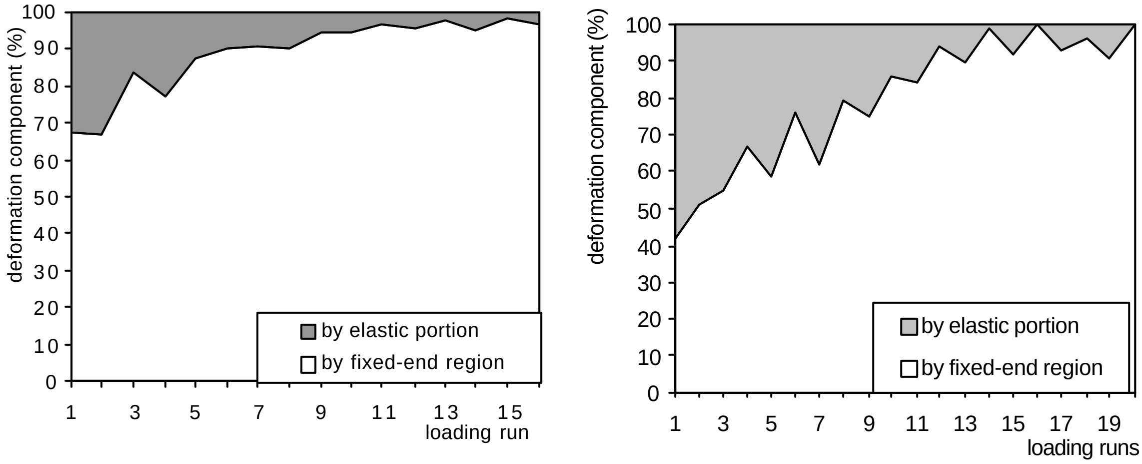
Regarding the beam deformation, the magnitudes of different deformation components are also studied. Figure 3 shows a few examples, where the deformation components were decomposed for the beam members. It is obvious that the main deformation source of the members is the fixed-end rotation, and the beam member itself can be treated as a rigid body, which rotates about its fixed-end. This suggests that the adequate modelling of the hysteretic behaviour at the fixed-end of the beam members will determine the reliability of the results of the structural post-elastic analysis.



(a) Unit EJ2, tested with zero column axial load

(b) Unit EJ4, tested with a compressive axial load of 0.25Agfc’

Figure 2. Displacement components measured for the test units as a whole



(a) Unit EJ2 beam.

(b) Unit EJ4 beam

Figure 3. Deformation components measured for the beam of the test units

The need for adequately modelling the hysteretic behaviour at the fixed-ends of a member is also supported by the evidence from the tests on reinforced concrete members reinforced by deformed longitudinal reinforcement. There have been frequent reports on the significant contributions due to member fixed-end rotation for the reinforced concrete subassemblages reinforced by deformed longitudinal reinforcement (Takeda et al. 1970, Lin et al. 2000 and Hakuto et al. 1995).

2.2 Mechanism of hysteretic behaviour at fixed-ends of a reinforced concrete member

Beam deformation in terms of the fixed-end rotation appears similar to the flexural deformation in beam plastic hinge region (PH) at the fixed end, which is of a very small length. The conventional beam flexural deformation in the plastic hinge region is assumed to be due to the steel yield penetration within the PH region, which is a portion of the beam itself. However, beam deformation in terms of the fixed-end rotation is mainly due to bond degradation along the longitudinal reinforcement within the joint core, and hence it is associated with the force transfer from the beam longitudinal reinforcement to the concrete within the joint core. This means that all the factors, which affect the member force transfer across the joint core, will also affect the hysteretic behavior at the fixed-end of the beams. Many factors influence the hysteretic behavior at the fixed-end of the beams, for example, the bond mechanism of the longitudinal reinforcement and the surrounding concrete, the stress level of the beam tensile longitudinal reinforcement at the beam-column interface, the actions imposed on the columns and the adjacent beam at the same joint, the joint shear reinforcement, so on. Use of deformed longitudinal bars or plain round longitudinal bars greatly affects the characteristics of the hysteretic behavior at the beam fixed-end.

Beam fixed-end deformation is greatly dependent on the strain profile of beam flexural reinforcement within the joint core. When the beam contains deformed longitudinal reinforcement, the strain profile of the beam flexural reinforcement within the joint core is greatly dependent on the effectiveness of the joint truss mechanism, as postulated in NZS3101: 1995. Hence, the arrangement of the joint shear reinforcement plays an important role in studying the flexural behavior at the fixed-end of the beam.

However, this is not the case when the beam contains plain round longitudinal reinforcement. The bond strength between the steel and the concrete in this case is so low that the shear flow type of force introduced into the concrete can not reach a point, which will crack the joint core concrete. Hence, the member force transfer across the joint cores is mainly by the diagonal concrete strut action. The truss mechanism, which starts to be active only after the concrete cracks, plays a very insignificant role. As a consequence, the stress level at the beam-column interface in the beam flexural tensile reinforcement will be basically the same until the beginning of the column flexural compressive region, and the sustained tensile strains in the beam flexural tensile reinforcement results in the big fixed-end rotation. Apparently, the extent of the column flexural compressive status determines, at a certain level, the magnitude of the beam fixed-end rotations. There are many factors, which influence the column flexural compressive depth and the compressive stress level, such as, the column overall depth and column moment action, column axial load so on. Among them, the column axial load might have the greatest influence on the column flexural compressive depth.

Fig. 4 compares the observed skeleton curve of the hysteretic behavior at the fixed-ends of the beam member for two tests, in terms of the moment capacity versus the rotation at the fixed-ends. The two tested units were identical as-built exterior beam-column joint subassemblages, one was tested subjected to simulated seismic loading with zero column axial load present, while the other one was tested subjected to simulated seismic loading with a compressive column axial load of $0.25A_g f_c$'present. Both units when tested showed that the post-elastic behavior of the systems was limited to the beam flexural behavior at the fixed-end. From Fig.4, it is clear that the presence of the compressive column axial load enhanced the flexural behavior at the beam fixed-ends, especially the stiffness performance.

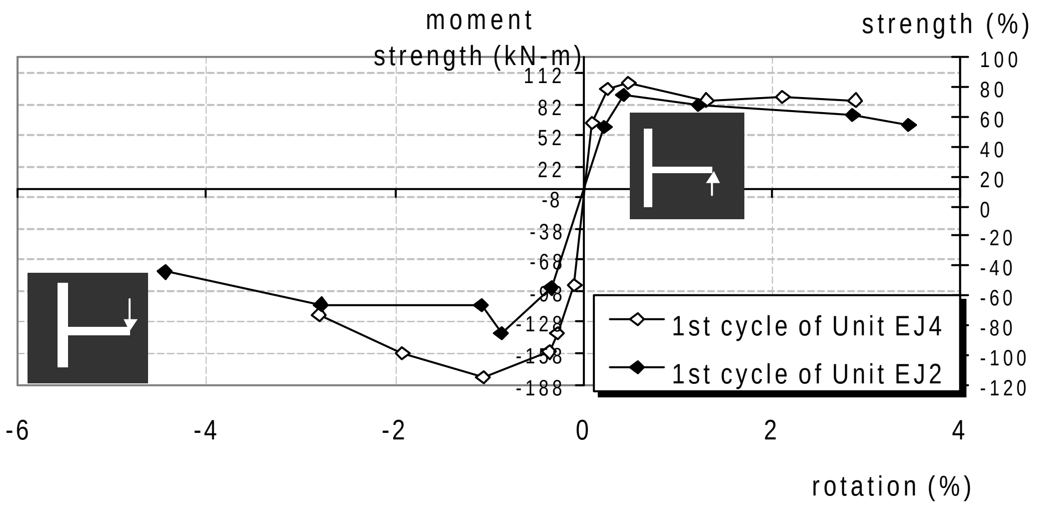
This is different from the post-elastic behavior in the plastic hinge regions, which assumes that the beam non-linear flexural deformation is due to steel yield penetration within beam plastic hinge regions, therefore the post-elastic behaviour of the beam member is completely determined by the beam itself, irrespective of the member force transfer within the joint core.

Therefore, beam flexural deformation in terms of the fixed-end rotation is fundamentally different from the flexural deformation in the beam plastic hinge region as ordinary flexural theory assumes. For the former one, the post-elastic hysteretic behaviour at the fixed-ends of the beam is not only dependent on the beam itself, but also is dependent on the members framed into the same joint. However, for the latter case, the post-elastic hysteretic behaviour within the plastic hinge regions of the beams is only dependent on the beam itself. Hence, a proper member model for reproducing the post-elastic behaviour at the beam fixed-ends should allow for the effects from the members framing into the same joint.

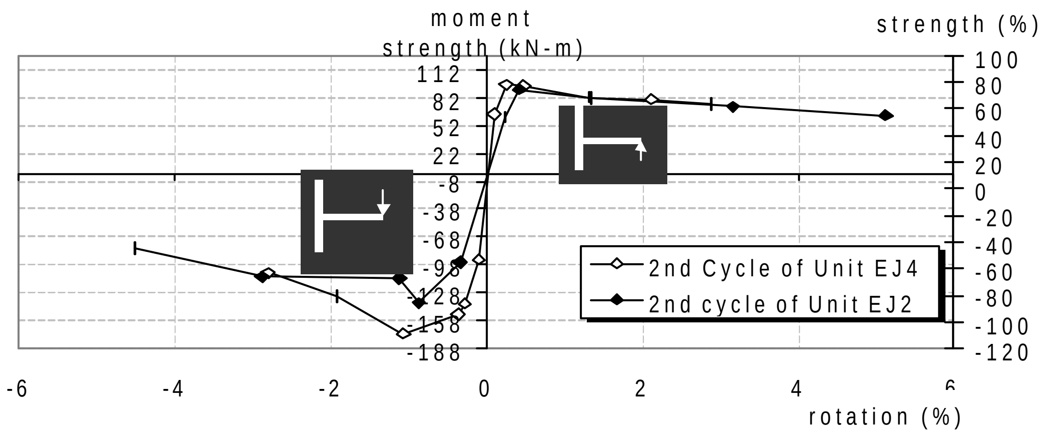
3 REVIEW OF EXISTING MEMBER MODELS

There are many models for the member non-linear flexural behaviour in the plastic hinge regions. The most widely used one is Giberson's one-component member model (Giberson 1967). Others include multi-spring models (Clough et al. 1966) so on. Typically, a flexural spring is inserted in the plastic hinges of a member to represent the non-linear flexural behviour and the remaining part is represented by an elastic element. Properties of the flexural spring and the elastic element are completely determined by the considered member. There is a member model, which consists of many sub-elements, and one sub-element is to capture the deformation characteristics related to the member fixed-end rotation (Filippou et al. 1999), but it does not allow for the effect from other members at the same joint. As a result, it does not really differ from other ordinary member models.

Apparently, there is a need for developing a proper member model, which is capable of capturing the effect of other members on the flexural behaviour at the fixed-end of the studied member, as observed evidence during simulated seismic loading tests.



(a) First loading cycle



(b) Second loading cycle

Figure 4. Comparison of strength and deformation capacity skeleton curves in the beam fixed-ends for Units EJ2 and EJ4

4 PROPOSED MEMBER MODEL FOR REPRODUCING THE OBSERVED EVIDENCE AT FIXED-END OF A REINFORCED CONCRETE BEAM

A member model was proposed in this study to capture the characteristics of the observed post-elastic behavior at the fixed-end of a reinforced concrete beam reinforced by plain round longitudinal bars.

As described in Section 2.2, a fundamental characteristic of the post-elastic behavior at the fixed-end of an as-built reinforced concrete beam member is its association with the member force transfer mechanism across the joint core. Hence, a joint member model should be ideal, but the definition of such a member model will require many parameters. This is especially true when the longitudinal reinforcement is from deformed bars. When the longitudinal reinforcement is from plain round bars, the major factor affecting the beam post-elastic behavior at the fixed-end is the axial actions on the columns at the same joint. To simplify the member modelling at the fixed-end of the beam, only the column axial load is considered in constructing the suggested member model at the beam fixed-end.

For the ordinary beam flexural spring, the spring is inserted into the assumed plastic hinge regions and its properties are determined completely based on the beam under study. The suggested member model also uses one flexural spring to model the beam fixed-end behaviour, but the properties of this specific spring are first determined by the beam under consideration, then are modified based on the column axial load level.

Figure 5 Proposed member model

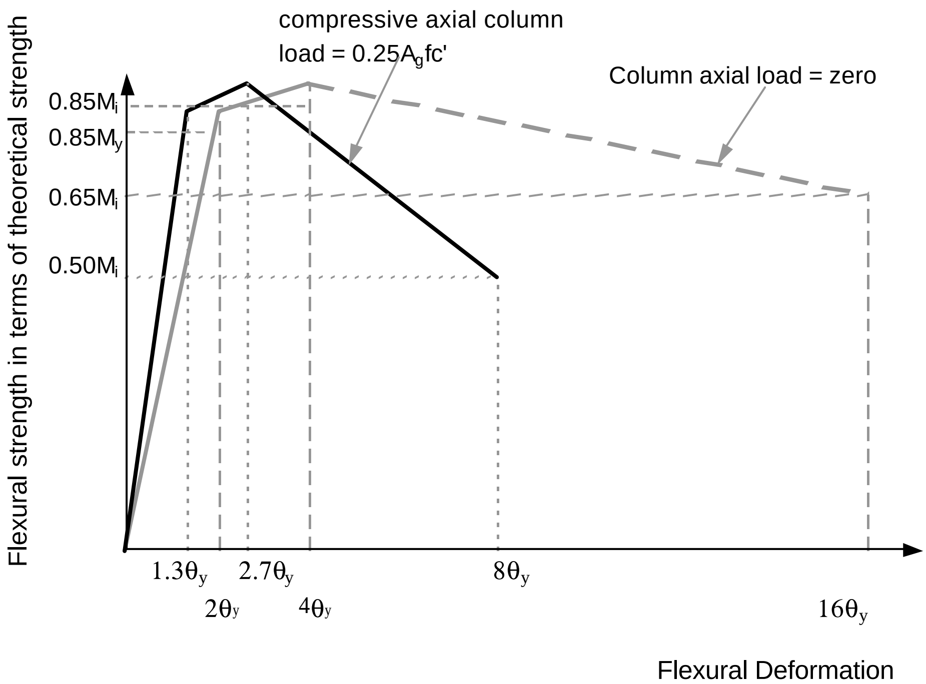


Figure 6 Generalised beam flexural strength versus rotation at fixed-end curves

The plane section assumption is significantly violated when severe bond degradation occurs along the member longitudinal reinforcement, but the determination of the beam hysteretic properties is still established on the benchmark of the results from plane section theory. Due to severe bond degradation along the longitudinal reinforcement, the attainment and the maintenance of the beam stiffness and strength are very low (Liu et al. 2002). Allowance for the poor attainment and maintenance of the strength and stiffness was based on the very limited test data. In addition, the beam non-linear behavior at the fixed-ends is modified based on the axial load of the column at the same joint, and such a modification is again only based on very limited test results.

Figure 5 shows the proposed member model, and it has the form of Giberson's one-component member model. The determination of the hysteretic properties, which allows for the effect of severe bond degradation along the member longitudinal reinforcement and the effect of the column axial load at the same joint, is seen in Figure 6, based on the test data. In Figure 6, M_i and M_y are respectively the theoretical flexural strengths at the ultimate limit state and at the first yield state, and θ_y is the fixed-end rotation calculated according to the theoretically predicted displacement at first yield. The maximum effect of the column axial load on the hysteretic behavior at the beam end at the same joint is taken as the value where the column compressive axial load is 0.25Agfc'. When the column compressive axial load level is between zero and 0.25Agfc', interpolation method should be used.

Implement of the proposed member model in the seismic assessment of the entire existing reinforced concrete building is exactly the same as the ordinary structural analysis, and hence is not described in detail here.

5 CONCLUSIONS

(1) The post-elastic behavior of as-built reinforced concrete structures with plain round longitudinal reinforcement is basically limited to the fixed-ends of the members. The post-elastic behavior in the fixed-ends of reinforced concrete members is characterized by its association with the member force transfer within the joint core. This means that it is associated with all the other members framing into the same joint as the member under study. This differs from the conventional member post-elastic behavior.

(2) A member model is proposed to represent the post-elastic behavior at the fixed-end of an as-built reinforced concrete member reinforced by plain round longitudinal reinforcement. For the proposed member model, the mechanism of the post-elastic behavior at the fixed-end of an as-built reinforced concrete member containing plain round longitudinal reinforcement is greatly simplified, and the determination of the hysteretic properties at the beam fixed-end only allows for the column axial load.

(3) Based on very limited test data, the determination of the static strength and deformation skeleton curves for the post-elastic behavior at the beam fixed-end is suggested, and allowance for the influence of column axial load is also tentatively suggested.

(4) This paper addresses the need for developing a proper member model for representing the fixed-ends of a reinforced concrete member, rather than tries to completely solve the problem. Apparently, further work needs to be done to more accuartely identify the influences of various parameters on the behaviour at the member fixed end, and therefore achieve a suitable member model for this specific case.

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