Dhakal, R.P. and Fenwick, R.C. (2009) *Closure: Detailing of plastic hinges in seismic design of concrete structures.* Discussion Paper

The authors would like to thank Dr Elmenshawi for his interest in the paper. Below are the authors' responses to the points raised by Dr Elmenshawi.

1. The discusser has confused the term "effective plastic hinge length" with the term "ductile detailing length". As defined in the paper, the effective plastic hinge length is used to determine a nominal maximum curvature in a plastic hinge, while the ductile detailing length is the length over which reinforcement may yield accompanied by concrete crushing and it is this length in which ductile detailing is required. Tests[8] have shown that in a plastic hinge zone reinforcement strains vary approximately linearly from a maximum value at the critical section of the plastic hinge to the yield strain at the low moment end, as shown in Figs. 4 and 5. Potential rotation capacity of plastic hinges is usually calculated on the basis of a uniform maximum curvature acting over an equivalent (effective) plastic hinge length[7,40,41] which is taken as half of the ductile detailing length to obtain the same plastic rotation as from the linearly distributed actual reinforcement strain profile. While many factors influence the length over which reinforcement yields for slender beams it is generally close to the depth of the beam, h. Hence, the effective plastic hinge length is generally of the order of h/2 for beams. For columns subjected to appreciable axial load the ductile detailing length can be significantly greater than h. However, as the assumed effective plastic hinge length (i.e. $l_p$=h/2) is used both in establishing the nominal curvature to be used as an index of the state of strain in a plastic hinge and in calculating the limiting curvatures from the test results, any difference between the assumed and actual ductile detailing lengths will be inconsequential.

2. The term material strain is used, as indicated in the paper, to be consistent with the Earthquake Actions Standard (NZS 1170.5)[1] which is used in conjunction with different material standards for concrete, steel, timber, aluminum etc. As indicated in some detail in the paper, it is difficult to calculate reinforcement and concrete strains in plastic hinge zones and such calculations are certainly inappropriate for practical design. As the discusser has mentioned, and also as discussed in the paper (see Fig. 5 and the associated text), the assumption that plane sections remain plane is not applicable for reversing plastic hinges. In addition, as discussed in the paper many beam tests[10] have shown that plastic hinges subjected to both negative and positive inelastic rotations elongate. Elongation of plastic hinges does not allow the cracks in the compression zone formed during the previous loading cycles to close and causes the strains in the compression zone to be tensile. Furthermore, there is the added complexity of shear deformation in plastic hinges, which as noted in the paper can be very appreciable and not easy to calculate. Calculations which ignore elongation and shear deformation and are based on plane sections remaining plane in a reversing plastic hinge lead to erroneous predictions of reinforcement concrete strains.

Currently New Zealand concrete code[3] specifies material strain limits for nominally ductile plastic hinges and curvature ductility limits for ductile and limited ductile plastic hinges (see Table 3). For nominally ductile plastic hinges limiting concrete and reinforcement strains are given as these zones are only permitted to sustain very limited inelastic deformation and little inelastic cyclic loading is likely to occur in them. However, as discussed in the paper concrete and reinforcement ductile members can sustain larger strains, which are difficult to be appropriately assigned for two reasons; firstly limiting strain levels depend on the level of confinement and restraint against buckling, secondly realistic strains cannot be calculated

unless realistic allowance is made for the influence of shear deformation and elongation in plastic hinges. For these reasons nominal curvature limits were established from experimental results for ductile and limited ductile plastic hinges.

3. Despite the discusser's objection, the authors maintain that curvature ductility (as interpreted in the paper) of 17.5 is an appropriate design limit. This level of curvature has been exceeded in majority of tests of ductile plastic hinges. The discusser indicates that a curvature limit of 5 is appropriate and he references 10 beam tests[32] that he conducted. The authors have examined these test results and they do not agree with the deductions the discusser has made from these. Before considering these test results, it is noted that the curvature limits described in the paper were proposed for use in New Zealand Concrete Standard[3] and consequently should only apply to plastic hinges satisfying the detailing requirements of this standard. Among the provisions in the New Zealand Standard[3] for reversing plastic hinges, the following are relevant to the detailing used in the 10 beams tested by the discusser[32].

- Limiting the maximum design strength of concrete to 100MPa unless a higher value is justified by a peer reviewed study. Hence, where a higher strength concrete is used a value of 100MPa is assumed in calculations;

- The maximum permissible spacing of stirrups in reversing plastic hinges is limited to the smaller of 6 times the diameter of longitudinal bar or ¼ of the effective depth of the beam;

- Where the shear stress exceeds the limit of $0.25(2+r)\sqrt{f_c'}$, diagonal reinforcement is required to prevent degradation in strength due to sliding shear (r is -1.0 for equal upward and downward shears);

- The minimum ratio of longitudinal compression to tension reinforcement in the beam is not allowed to be less than 0.5 in ductile and 0.38 in limited ductile plastic regions;

- Reinforcement complies with the appropriate combined Australian/New Zealand Standard.

Of the ten beams referred by the discusser[32], four had strengths in the range of 150 to 175MPa and hence in considering these units the concrete strength was taken as 100MPa. Three beams contained three 10mm bars on the bottom and three 20mm bars on the top, which results in a bottom to top reinforcement area ratio of 0.25, which is inconsistent with both the NZ and ACI structural codes. In addition the spacing of stirrups in these beams corresponded to 10 times the diameter of the longitudinal bar ($10d_b$) while the New Zealand code gives a limiting value of $6d_b$ (the corresponding limit in ACI 318 is $8d_b$). In seven of the beams the spacing of stirrups exceeded the limit of d/4, and in four beams the limit on sliding shear was exceeded. In one beam, the load deflection curves showed no strength degradation; hence a limiting curvature could not be calculated. The longitudinal reinforcement used in the beams had a high strain hardening potential with the ratio of maximum strength to yield strength of the order of 1.6. The New Zealand Standard requires this ratio to be less than 1.4.

Despite all these deficiencies, the authors' calculations showed that the curvature ductility sustained the beams tested by the discusser[32] exceed the proposed limit of 17.5. The authors calculated the limiting curvatures from the reported load deflection curves for six of these beams, excluding four beams which showed no strength degradation and in which the ratio of bottom to top reinforcement areas was 0.25. Based on the methodology applied in the paper, the elastic displacements and maximum displacements attained before the strength degraded to 80% of the maximum shear were measured from the load displacement figures

for each test.  As shown in Table 4, the average limiting curvature for the six beams was

21.7, with the minimum and maximum values being 18 and 26.5, which in the light of the

sub-standard detailing, is reasonably consistent with the values proposed in the paper and far

in excess of the discusser's suggested limit of 5.

Table 4- Calculation of curvature ductility for beams tested by the dicusser[32]

| Test unit | $\Delta_{max}$ | $\Delta_y$ | L | $\theta_p$ | $\phi_p$ | $\mu_\phi$ |
|---|---|---|---|---|---|---|
| N-1.0-01.6-3 | 53 | 11 | 854.5 | 0.049 | 0.00028 | 20.9 |
| U-1.0-1.6-3 | 59 | 9 | 854.5 | 0.058 | 0.00033 | 24.5 |
| N-1.0-0.8-2 | 29 | 6 | 558 | 0.041 | 0.00029 | 21.7 |
| H-1.0-0.8-2 | 35 | 7 | 558 | 0.050 | 0.00036 | 26.5 |
| U-1.0-0.8-2 | 25 | 6 | 558 | 0.034 | 0.00024 | 18.1 |
| U-1.0-0.8-3 | 46 | 9 | 854.5 | 0.043 | 0.00025 | 18.3 |
| | | | | | Average= | 21.7 |

$\Delta_{max}$: Maximum deflection (corrected to account for the number of cycles) before the strength
       dropped to 80% of the maximum strength;
$\Delta_y$: Elastic deflection interpreted from the load displacement curves;
L: Length from the centre of plastic hinge to the load application point;
$\theta_p$: Plastic rotation = $(\Delta_{max} - \Delta_y)/L$;
$\phi_p$: Plastic curvature = $\theta_p/L_p$;
$\mu_\phi$: Curvature ductility ($\mu_\phi = \phi_u /\phi_y$;  $\phi_y = 2\varepsilon_y /h$)

4.  The calculation based on maximum plastic rotation $\theta_p = 0.02$ radians is misleading.  As can

be seen in Table 4, the plastic rotation for the beams tested by the discusser, despite not

satisfying all detailing requirements for ductile reversing plastic hinges, is more than 0.04

except for one beam.  Even for beams detailed as nominally ductile plastic hinges, the plastic

rotations measured in tests[42] were more than 0.02.  The authors have witnessed much higher

plastic rotations sustained by ductile reversing plastic hinges.  If higher values are used for

plastic rotations in Equation (3), the calculated maximum curvature will be in the same range

as the curvature limits suggested in the paper.

5. The authors agree that the contribution of shear deformation can be significant and this was discussed in some detail in the Discussion section in the paper.

6. The discusser has misunderstood the scope of Equations (1) and (2). Both of these equations are for plastic hinges developing in beams; i.e. they correspond to Fig. 2a. For cases where plastic hinges develop in columns, the plastic rotation can be derived as $\theta_p = \delta_{i,p}/h'$ using Fig. 2b. Even for the beam plastic hinge case, if the heights and drifts of the two stories are assumed to be equal and L'/L=h'/h for simplification, combining Equations (1) and (2) will also result in $\theta_p = \delta_{i,p}/h'$, which is same as for column plastic hinge case. Hence, having equal curvature ductility limits for beam and column plastic hinges is not incorrect.

7. The authors agree that the reinforcement properties, among others, influence the ductility sustained by reinforced concrete elements. It is for this reason that different limits are provided for the three categories of plastic hinges (namely ductile, limited ductile and nominally ductile), which are classified based on amount and arrangement of longitudinal and transverse reinforcement. In addition, even for a given type of plastic hinge, yielding properties of reinforcement ($\varepsilon_y$, $f_y$, $K_y$) are used in the calculation of the limits.

**References**

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