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STRENGTH DETERIORATION MODEL BASED ON EFFECTIVE HYSTERETIC ENERGY DISSIPATION FOR RC MEMBERS UNDER CYCLIC LOADING

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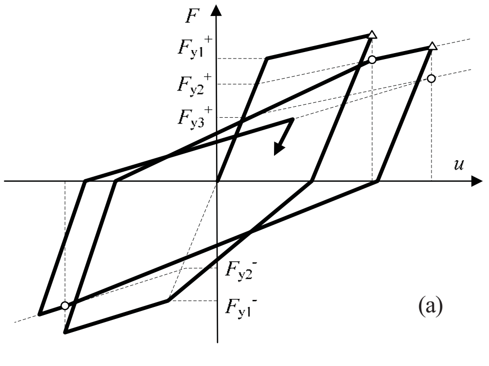
Abstract: In simulating the nonlinear seismic behavior of RC structures subjected to strong earthquake ground motions, it's necessary to take into account the effects of accumulative damage of structural members, of which the strength deterioration is one of the most important aspects. By examining the influence of loading histories on the strength deterioration, it is shown that the extent of damage caused by a certain amount of hysteretic energy is dependent on the displacement amplitude at which the energy is dissipated. The effective hysteretic energy dissipation is defined through combining the hysteretic energy dissipation with its corresponding displacement amplitude. It is proved by calibrating with existing test data that the effective hysteretic energy dissipation shows good correlation with the extent of strength deterioration, and that the proposed strength deterioration model is effective in simulating the hysteretic behavior of reinforced concrete members subjected to various cyclic loading histories.

1. INTRODUCTION

It is of crucial importance to accurately estimate the seismic performance of building structures in performance based seismic design. Observations in structural experiments as well as earthquake reconnaissance implied significant influences of loading histories on the dynamic behavior of structures. Structural members are subjected to various deteriorations during earthquake ground motions, to which the failure of individual members or even the whole structure can be attributed, especially when subjected to long-duration ground shakings with many large-amplitude load reverses. An adequate model to simulate the structural nonlinear dynamic responses should be capable of capturing these features. The present paper will focus on the strength deterioration of reinforced concrete (RC) members.

The mechanism of strength deterioration of RC members is commonly interpreted by concrete spalling and interface bond slip between the concrete and embedded reinforcements. In the celebrated damage model for RC members proposed by Park and Ang (1985), cumulative damage is dependent on a linear combination of the maximum displacement and the cumulative hysteretic energy dissipation. However, only one of the two factors is generally incorporated in existing strength deterioration models in the literature, say some models are based solely on the maximum displacement, such as models in Lai *et al* (1984), Roufaiel and Meyer (1987), Chung *et al* (1989) and Yousseef and Ghobarah (1999), while others on the cumulative energy dissipation, such as in Kunnath *et al* (1990), Mork (1991), Rahnama and Krawinkler (1993) and Sucuoglu and Erberik (2004).

The bilinear peak oriented hysteretic model as shown in Figure 1 provides a common basis for all the existing strength deterioration models. The strength deterioration can be expressed either by softening the skeleton curves (Figure 1a) or moving the reloading oriented points (Figure 1b). In Figure 1, F_{yi} refers to the yield strength at the *i*th loading cycle; Δu_{o} and ΔF_{o} refer to the change of displacement and force of the oriented point, respectively. Triangles and circles indicate the maximum displacement point and the reloading oriented point in a loading cycle, respectively.



(a)

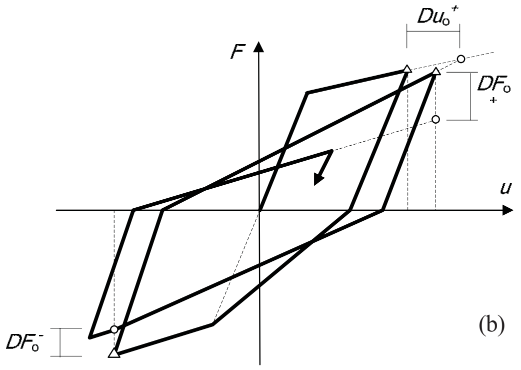


Figure 1 Strength deterioration in peak oriented hysteretic model: (a) Soften the skeleton curve, and (b) Move the reloading oriented point

2. INFLUENCE OF LOADING HISTORIES ON STRENGTH DETERIORATION

To better understand the influences of the maximum displacement or the cumulative hysteretic energy dissipation on the strength deterioration, existing experimental data are re-examined focusing on the influence of various loading histories.

Displacement loading with monotonically increased amplitude is the most commonly used loading scheme in studying the cyclic behavior of structural members while constant amplitude loading is another important scheme especially when the low cycle fatigue performance is of major concern. The structures are however subjected to neither a monotonically increased-amplitude nor a constant amplitude loading during a ground shaking. Large uncertainties exist in the loading histories, which may have significant influence on the deterioration behavior of structural memberes.

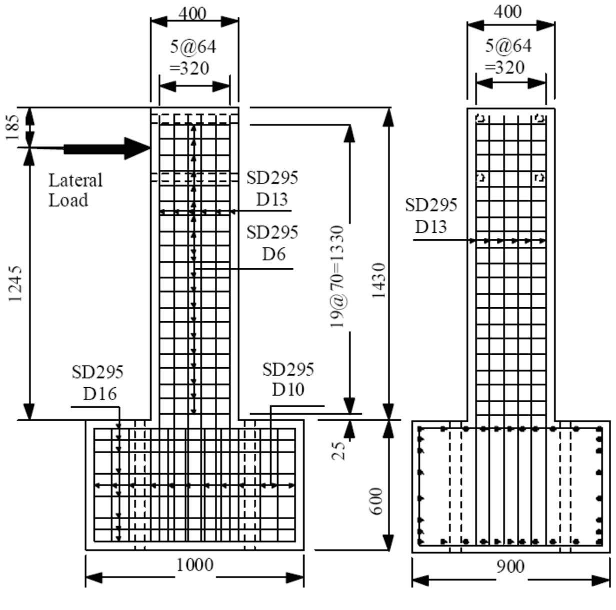


Figure 2 Dimension and reinforcement of the specimen (Figure 1 in Takemura 1997)

Such an influence on the seismic performance of RC bridge piers were studied by Kawashima and Koyama (1988) through large-scale high-speed loading tests. Results showed that severer damage could be expected if the specimens are loaded with monotonically decreasing, rather than increasing, displacement amplitudes. The influence of loading histories on the plastic deformability of bridge piers was further studied by Takemura and Kawashima (1997). In their test, six identical specimens, as seen in Figure 2, were subjected to cyclic loadings with different loading histories. The specimen was a cantilever column with a height of 1245mm from the surface of foundation to the loading point and a cross section of 400mm square. The effective depth of the cross section was 360mm leading to a nominal shear span-to-depth ratio of 3.46. The average concrete strength was about 35MPa. D13 rebars with yield strength of 363MPa were adopted for the longitudinal reinforcement and D6 rebars with yield strength of 368MPa and 70mm spacing for stirrups. Longitudinal reinforcement ratio was 1.66% and stirrup ratio about 0.2%. A constant axial compression of 157kN, about 3% of the column's maximum compressive strength, was applied at the top. Specimens identified as TP001~TP006 were then subjected to lateral load with 6 different histories as shown in Figure 3.

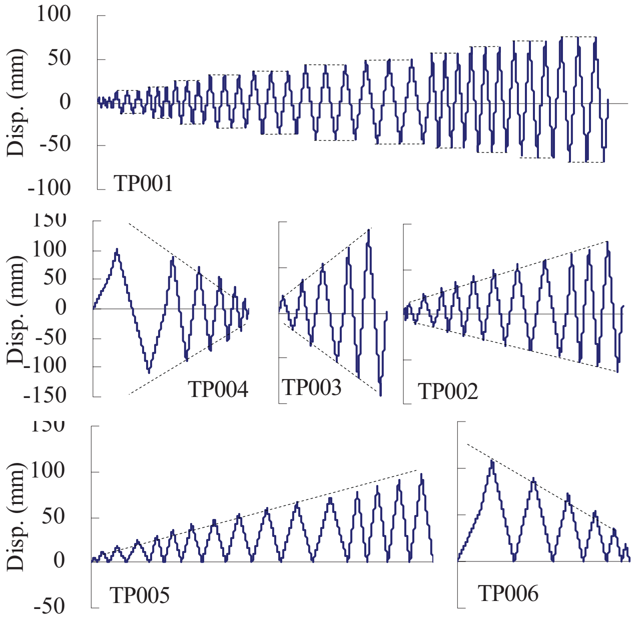


Figure 3 Loading hysteresis in Takemura test (rearranged from Figure 2 in Takemura 1997)

Compared with the yield strength of the skeleton curve (i.e. F_{yi} in Figure 1a) or the change in displacement of oriented point (i.e. Δu_o in Figure 2b), the force of the oriented point in subsequent loading cycles, denoted as F_{oi} in Figure 4, can be readily obtained from the test data without too much idealization of the experimental hysteretic curves. Take TP003 and TP004 for examples. For specimens subjected to displacement cycles with increasing amplitudes, such as TP003, F_{oi} is simply the force achieved at the maximum displacement of the last loading cycle in the same direction (See Figure 4a). For specimens subjected to loadings with decreasing amplitudes, such as TP004, F_{oi} can be taken as the force on the tangent of the hysteretic curve when it reaches the maximum displacement of the last loading cycle in the same direction (Figure 4b).

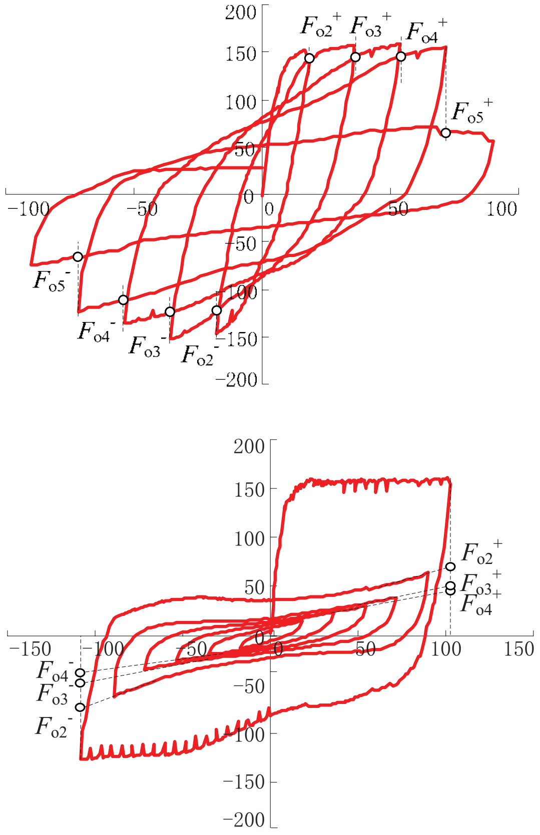


Figure 4 Determination of the forces of oriented points: (a) TP003-Monotonically increasing amplitude, and (b) TP004- Monotonically decreasing amplitude

Through such a manner, forces of the oriented points F_{oi} are obtained for all the six specimens in both loading directions. The dependencies of F_{oi} on the maximum displacement in the last cycle u_{i-1} and the cumulative hysteretic energy ΣE_i for the six specimens are compared in Figure 5. A general trend for specimens with increasing loading amplitudes (TP001, 2, 3 and 5) can be observed that the force of the oriented point F_{oi} drops with the increase of u_{i-1} or ΣE_i. But the story is somehow different for other specimens (TP004 and 6) in that their forces of the oriented points F_{oi} drop with the decrease of u_{i-1} (Figure 5a). This implies that u_{i-1} is not an adequate index to describe the strength deterioration. In addition, large scattering of the relations between forces of the oriented points and cumulative energy dissipations is observed in Figure 5b for specimens subjected to different loading histories despite that their forces of the oriented points perform similar decreasing trends with the increase of cumulative energy dissipation. This further indicates that the cumulative energy dissipation doesn't well represent the strength deterioration either.

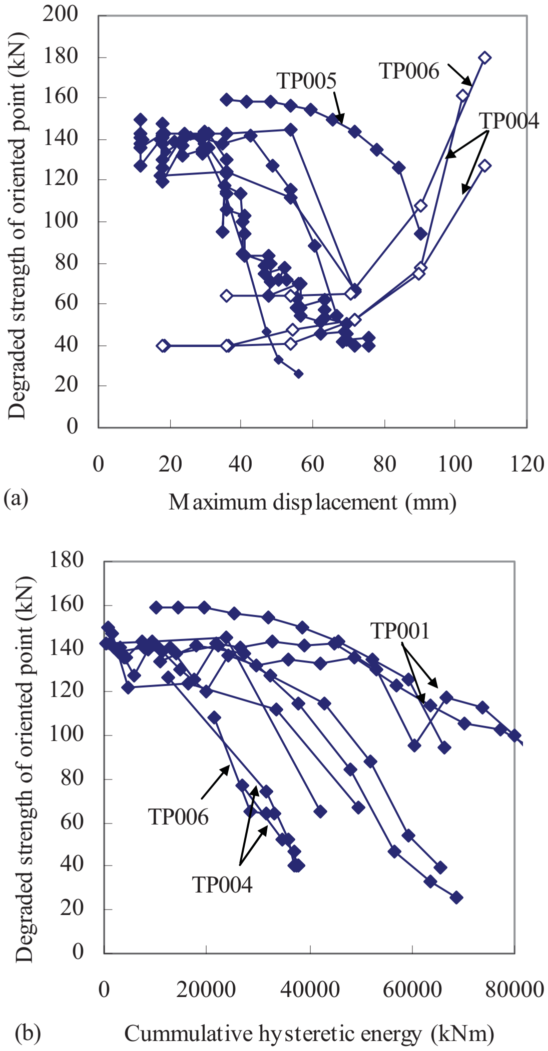


Figure 5 Dependency of the force of oriented points on (a) maximum displacement and (b) cumulative energy dissipation

3. EFFECTIVE HYSTERETIC ENERGY DISSIPATION

Liu *et al* (1998) obtained the relationship between the loading displacement amplitude and the low-cycle fatigue life of RC members through a series of constant-amplitude cyclic loading test. Results showed that the low-cycle fatigue life of an RC member became dramatically shorter and the cumulative energy dissipation needed to cause the failure of the member was smaller when the constant-amplitude loading was carried out at larger amplitude. These results confirm the observations made in Figure 5(b), where, for example, the cumulative energy dissipations to reduce the forces of the oriented points to the same level are much smaller for TP004 and TP006, which were loaded at first with large displacement amplitudes followed by decreasing amplitudes, than for TP001, which was loaded with increasing amplitudes. It can be therefore concluded that the strength deterioration of an RC member subjected to cyclic loading at smaller amplitude can be expected less severe than that at large amplitude provided the cumulative hysteretic energy dissipations are the same. Based on these findings, the so called "effective hysteretic energy dissipation" is proposed as in Equation 1.

$$E_{\mathrm{eff},i} = \sum_{j=1}^{i} \left[E_j \cdot \left(\frac{u_j}{u_{\mathrm{f}}} \right)^2 \right] \quad (1)$$

where $E_{\mathrm{eff,i}}$ is the effective hysteretic energy dissipation up to the ith loading cycle; u_{j} is the displacement amplitude of the jth cycle; u_{f} is the ultimate displacement of the member; E_{j} is the hysteretic energy dissipation in the jth cycle.

It is clearly seen from Equation 1 that the energy dissipation at large displacement amplitude will contribute more to the effective hysteretic energy dissipation.

Figure 6 depicts the relationship between the forces of the oriented points F_{o} and the effective energy dissipation E_{eff} (Equation 1) for the six specimens in the previous discussion, where F_{o} and E_{eff} are normalized by the initial yielding strength F_{y1} and the product of F_{y1} and u_{f}, respectively. It is seen that the large scattering in Figure 5 is significantly reduced, indicating that the content of strength deterioration is strongly correlated with E_{eff}.

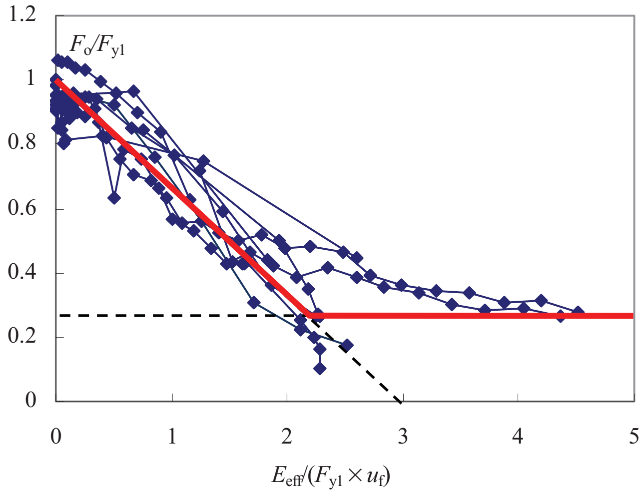


Figure 6 Dependence of the forces of oriented points on effective hysteretic energy dissipation

The bilinear relation in Equation 2 (shown as the bold line in Figure 6) is suggested to idealize the experimental results.

$$\frac{F_{\mathrm{o}i}}{F_{\mathrm{y1}}} = 1 - \frac{E_{\mathrm{eff},i}}{\lambda F_{\mathrm{y1}} u_{\mathrm{f}}} \geq cF_{\mathrm{y1}} \quad (2)$$

where F_{oi} is the force of the oriented point for the ith loading cycle; λ and c are parameters determined from the test. For Takemura (1997) test, it is suggested that λ=3.0 and c=0.3 as shown in Figure 6. It is worth noting that these values are determined from test results of RC bridge piers subjected to very small axial compressions. This is generally not realistic for columns in building structures. Besides, other factors such as the amount of confinement and the concrete grades may also have major effects on the strength deterioration behavior of RC members. Hence the evaluation of λ and c deserves further research based on extensive experimental data.

For a hysteretic model with bilinear skeleton curve as in Figure 1(a), a quantitative relationship between the change in forces of oriented points ΔF_{oi} and the change in yield strengths ΔF_{yi} can be readily obtained as in Equation 3.

$$\Delta F_{\mathrm{o}i} = \frac{\Delta F_{\mathrm{y}i}}{1-\alpha} \quad (3)$$

where α is the ratio of post-yield to initial stiffness.

Substituting Equation 3 into 2 yields the following strength deterioration model in terms of the yield strength of bilinear skeleton curve (Equation 4).

$$F_{\mathrm{y}i} = F_{\mathrm{y1}} \left(1 - \frac{E_{\mathrm{eff},i}}{\lambda F_{\mathrm{y1}} u_{\mathrm{f}} (1-\alpha)} \right) \geq cF_{\mathrm{y1}} \quad (4)$$

In this model, the yield strength in the ith cycle F_{yi} is reduced in proportion to the current effective energy dissipation $E_{\mathrm{eff,i}}$.

4. MODELING OF STRENGTH DETERIORATION OF RC MEMBERS

For its capability of simulating the bending and axial force interaction and applicability of modeling members with various cross-section profiles and reinforcements, beam elements with fiber section are widely used in simulations of structural seismic behavior, in which the cross section of the element is divided into many segments (fibers) to which various mechanical properties can be assigned. With some modifications, the above-proposed deterioration model for the yield strength of skeleton curve (Equation 4) can be applied in fiber beam elements.

As mentioned before, the macro phenomenon of strength deterioration of RC members is a consequence of the meso-scale behavior including the bond-slip between rebar and concrete as well as the spalling of concrete cover. In studying their effects on the strength deterioration, Youssef (1999) adopted a four-rebar model as described in Lai (1984) and modified the hysteretic behavior of the rebar to simulate the strength deterioration, leaving the concrete hysteresis unchanged as that in non-deteriorating models. Comparisons between the analysis and test results showed that such a manner was effective in simulating the strength deterioration of RC members. This is not surprising since the modeling of rebar is predominant in simulating the behavior of RC members especially when significant plastic deformation is sustained. It is hence suggested that the above-mentioned strength deterioration model based on the effective energy dissipation can also be applied to fiber beam elements by simply replacing the force and displacement in Equation 1 and 4 by stress and strain of the rebar fibers as in Equation 5. In this manner, the strength deterioration of the beam element is taken into account by reducing the yield strength of the rebar in accordance with its "effective dissipated energy density" as defined in Equation 5(b). Note that this reduction is not the deterioration of the rebar itself, but represents the overall effect of interface bond-slip and the concrete spalling.

$$\sigma_{yi} = \sigma_{y1}\left(1-\frac{E_{\mathrm{eff},i}}{\lambda\sigma_{y1}\varepsilon_{\mathrm{f}}\left(1-\alpha\right)}\right)\geq c\sigma_{y1} \qquad (5a)$$

$$E_{\mathrm{eff},i}=\sum\left[E_i\cdot\left(\frac{\varepsilon_i}{\varepsilon_{\mathrm{f}}}\right)^2\right] \qquad (5b)$$

where ε_{f} can be taken as the maximum strain of the rebar when the member is monotonically loaded to its maximum displacement u_{f}.

The deterioration model in Equation 5 is built into an in-house user-material package based on the general purpose program ABAQUS 6.7-1, by which the cyclic responses of the six specimens in Takemura (1997) test are simulated. The non-deteriorating hysteresis of steel rebars and concrete in the package is depicted in Figure 7. The yield strength of the steel rebar will be updated during the analysis in accordance with Equation 5 when the strength deterioration is taken into account.

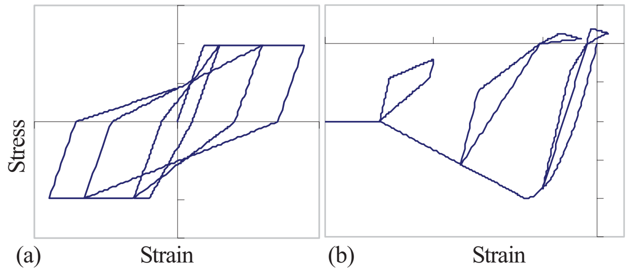
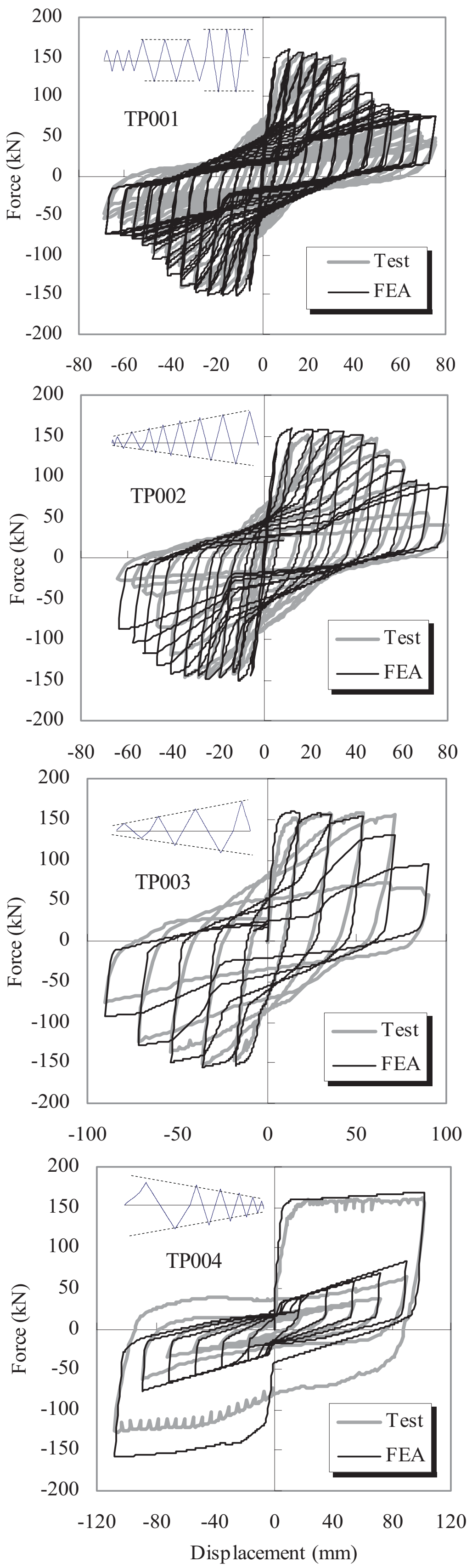


Figure7 Hysteretic models of (a) steel rebar and (b) concrete

The analysis results are compared with the test in Figure 8 for each of the six specimens. It is shown that the strength deterioration revealed by the analysis generally agrees well with the test results for most cases no matter the cyclic loadings are applied with increasing or decreasing amplitude. An exception is however observed for test TP005 where the estimated strength deterioration by the analysis is much severer than in the test. Note that the strength deterioration of TP005 was much delayed in the test as compared to its counterpart TP002, which was also loaded with increasing amplitude but in both directions. It is doubtful whether the strength deterioration could be so dramatically different between members subjected to one-way and two-way cyclic loadings before more experimental results are examined.



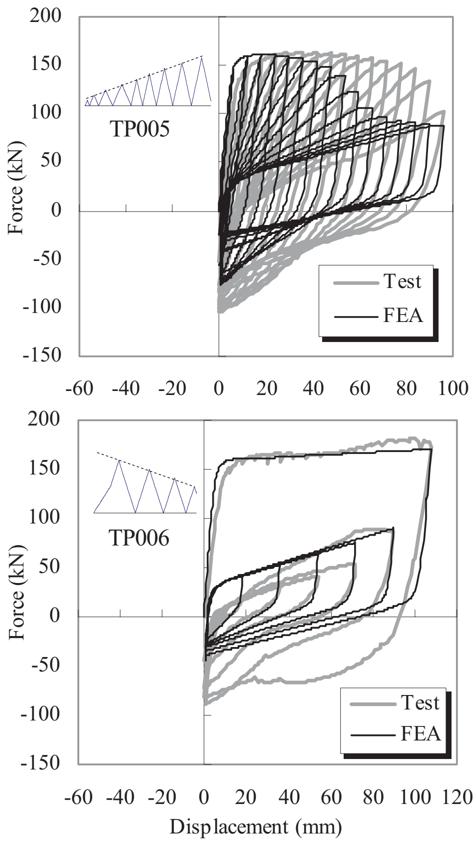


Figure 8 Comparison between the analysis and experimental results of Takemura 1997 test

5. CONCLUSIONS

The influence of loading histories on the strength deterioration of RC members is studied and the "effective hysteretic energy dissipation" is proposed as the controlling quantity influencing the content of strength deterioration, based on which a strength deterioration model is established. Through the above discussions, the following conclusions can be drawn:

(1) Loading histories have major effects on the strength deterioration of RC members. Cyclic loadings with decreasing amplitude are likely to cause severer strength deterioration than those with increasing amplitude.

(2) The proposed "effective hysteretic energy dissipation" integrates the hysteretic energy and maximum displacement in a concise form and well describes the dependency of strength deterioration on loading histories, as is evident from the fact that the effective hysteretic energy dissipation is strongly correlated with the content of strength deterioration for a series of tests with various loading schemes.

(3) It is effective to model the strength deterioration with fiber beam elements by adapting the proposed strength deterioration model and introducing it into the hysteresis of rebar fibers.

It is however worth noting that the evaluation of key parameters in the proposed strength deterioration model, say λ and c, still needs more experimental calibration in order to make it widely applicable to various types of structural members.

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