The discussers commend the authors for presenting a stimulating paper on the stress-strain model describing the behavior of reinforcing ribbed steel bars that affects the postyield response of reinforced concrete (RC) elements. The formulation presented in the paper is based on the Chang and Mander (1994) model in which buckling is introduced by adopting the Dhakal and Maekawa (2002) model. The discussers, however, believe that it could be important to assess the potential of the proposed model with respect to reinforcing smooth steel bars; this type of bar characterizes many existing RC-framed structures that have been designed without seismic provisions, and they are now located in high seismic zones. The model proposed by the authors is herein applied to reinforcing smooth steel bars characterized by specific L/D ratios corresponding to absence of buckling (i.e., L/D=5), buckling occurring between yielding and hardening strain (i.e., L/D=11), and buckling occurring close to yielding practically with no hardening (i.e., L/D=15).

The case of L/D=5 is first discussed comparing Fig. 1(a) the model outcomes to the mean experimental behavior of smooth bars Prota et al. 2009. The comparison depicted in Fig. 1(a) allows observing that the main discrepancy seems to be due to the curvatures of half cycles; therefore, the model proposed by the authors could be modified by replacing the curvature parameter given by Chang and Mander with that proposed by Menegotto and Pinto (1973). The cyclic curve given by the so modified model is compared to that experimental in Fig. 1(b) in which the Menegotto and Pinto curvature parameter has been determined using \( R_0=20, A_1=18.5, \) and \( A_2=0.001 \). Based on the aforementioned comparison, it seems appropriate to suggest that, if no buckling occurs, the cyclic behavior of smooth reinforcing bars could be simulated by using the model proposed by authors in which the Menegotto and Pinto curvature parameter is adopted in lieu of that given by Chang and Mander.

![Fig. 1. Comparison for smooth bars with L/D=5: (a) model proposed by authors; (b) model proposed by Cosenza and Prota (2006)](image)

![Fig. 2. Model proposed by authors versus experimental curves for smooth bars: (a) L/D=11; (b) L/D=15](image)
The typical behavior of smooth reinforcing bars in which buckling occurs between yielding and hardening strain or close to yielding with no hardening are then discussed with respect to the buckling occurs between yielding and hardening strain or close to buckling and the extension of the cyclic behavior tends to become nonsymmetrical (Prota et al. 2009). The predictions provided by the model proposed by the authors are compared to the experimental curves (Prota et al. 2009) in Fig. 2; these comparisons point out that, when buckling occurs, the extension of the proposed model to smooth reinforcing bars could require some modification not only concerning curvatures but also strength of the compressive branch. Therefore, the following modifications are proposed to extend the model proposed by authors to smooth reinforcing bars subjected to buckling, and the outcomes of the so modified model are compared to the experimental curves in Fig. 3:

1. Predict the compressive envelop curve by replacing the Dhakal and Maekawa model with that developed for smooth reinforcing bars by Cosenza and Prota (2006); and
2. Compute the curvature parameters of tensile and compressive branches by means of Chang and Mander, and Menegotto and Pinto relationships, respectively.

The writers thank the discussers for their interest in our work. In the following closure, in addition to addressing the particular issue raised by the discussers of applying the model to simulate the cyclic response of smooth reinforcing bars, the writers also take this opportunity to clarify an additional issue related to the use of natural stress-strain coordinates in developing the proposed model.

Influence of Buckling Model on Cyclic Response

The discussers apply the proposed model to simulate the response of smooth reinforcing bars and show that the initiation of buckling and the resulting shape of the stress-strain curve on the compression side are not effectively simulated. This is attributed to two factors: the parameter that controls the curvature of the stress-strain curve in the peak compression region; and the strength of the compressive branch for larger L/d ratios. Hence the discussers recommend (a) using calibrated curvature param-

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eters in the model developed by Menegotto and Pinto (1973) on the compression side and possibly retaining the relationships of the Chang and Mander (1994) model on the tension side; and (b) replacing the model of Dhakal and Maekawa (2002) with the model proposed by Cosenza and Prota (2006) for the case of smooth bars.

The writers acknowledge that the details of the curvature parameters were not specifically described in the paper since complete information is reported in the work of Chang and Mander (1994). It appears that the discussers used the default parameters given by Chang and Mander to produce the stress-strain responses whereas the model implemented in OpenSees (2009) contains a user-definable parameter $R$ which is composed of three variables $R_1$, $R_2$, and $R_3$ as follows

$$ R = R_2 (1.0 - R_3 e_y) e_y^{R_1} $$

where $e_y$ denotes the total half cycle strain amplitude; and $e_y$ denotes the strain at yield stress.

The resulting parameter $R$ provides greater flexibility in controlling the curvature as a function of the strain amplitude. In all the simulations reported in the paper, default parameters ($R_1 = 0.333, R_2 = 18$, and $R_3 = 4$) were used. The effect of the curvature parameter $R_2$ is illustrated in Figs. 1 and 2. In Fig. 1, we plot a set of arbitrary cyclic responses changing the default value of $R_2$ from 18 to 35. In this case, buckling parameters are not specified. The same cyclic responses are replotted in Fig. 2 with the change from 18 to 35. In this case, buckling parameters are not specified.

Hence, the main discrepancy between the prediction using the proposed model and the smooth bar experimental response is not necessarily due to the curvature parameter. The Chang–Mander model is essentially based on the Menegotto–Pinto approach for curve-fitting and therefore also contains parameters to control the shape and curvature of the stress-strain response as described above. It should further be mentioned that the curvature parameter provides a means to incorporate the well-known “Bauschinger effect”—a feature of steel stress-strain response that was shown by Restrepo-Posada et al. (1994) to be dependent on the carbon content of the steel alloy.

The writers agree that the strength in compression is influenced by the initiation of buckling which in turn is affected by the previous strain history of the bar particularly yielding in tension. These observations are confirmed in tests reported both by Dhakal and Maekawa (2002) and Prota et al. (2009), the former for the case of deformed bars and the latter for smooth bars. The writers further agree that the Dhakal–Maekawa model may not be adequate to simulate the buckling response of smooth bars where strength loss due to softening appears to be less significant than in the case of deformed bars. Likewise the model proposed by the discussers may not be appropriate to simulate the cyclic response of deformed bars. Nevertheless, the writers contend that the Dhakal–Maekawa model is appropriate for general application since it reasonably represents the buckling behavior of deformed bars and can be conservative when applied to smooth bars. Moreover, the objective of the paper was to develop a general phenomenological model with essential features that characterize the cyclic behavior of reinforcing bars. As indicated in the concluding remarks of the original paper, further enhancements to the buckling model are still needed to represent more completely the range of possible responses due to a variety of factors including but not limited to: the effect of tensile strains on buckling initiation and the role of confining reinforcement in controlling the effective $L/d$ ratio of longitudinal bars in reinforced concrete (RC) elements. The response of individual bars provides only part of the information necessary to develop and calibrate cyclic response models for reinforcing bars in RC structures.

**Response in Natural Stress-Strain Coordinates**

The writers also wish to use this opportunity to clarify the representative bounding stress-strain curves shown in Fig. 1 of the paper. The figure shows the slope of the curve in natural coordinates to remain positive while softening (due to necking) is observed in the tensile response in engineering coordinates. Likewise, softening due to buckling is shown in the compression envelope in engineering space while a positive slope is retained in natural coordinates. One of the readers asked for clarification of this behavior (Restrepo, personal communication, 2009).

First, the writers wish to make clear that the conceptual repres-
sentation in Fig. 1 was meant to illustrate basic concepts without attempting to demonstrate a “true” transformation of the engineering to natural coordinate system. The apparent discontinuity in the slopes of the curves at the peak points is misleading. This particular “conceptual” feature was introduced to indicate that true stress and strain are unlikely to exhibit softening though an examination of the material behavior at the microscopic scale is beyond the scope of this paper. The actual transformation is shown herein in Fig. 3 where Eqs. (1)–(2) of the original paper have been applied to the stress and strain values. As shown in the figure, the stress-strain curves in the natural coordinate system are symmetric and the observed softening in the engineering response is also reproduced in the natural system. Again it is emphasized that the application of Eqs. (1) and (2) is simply based on preservation of the volume of the material and not to be interpreted as an exact representation of behavior in the postpeak range. The postpeak softening response is typically observed in a tension test due to necking, which is a localized behavior, while softening in compression can occur only due to buckling (which is a geometric effect). The equations that transform engineering to natural coordinates are strictly valid only up to the point where the material is not influenced by the effects of localized damage such as necking in tension and buckling in compression. Hence, the true material behavior following nonuniform local deformation needs to be established through different approaches.

The strain-strain data used in the simulation is from an actual tensile test of a #11 reinforcing bar. It should also be pointed out that the stiffness of the tensile stress-strain response in natural coordinates is marginally higher but the inflection point from hardening to softening lags behind the corresponding stiffness in engineering coordinates. The reverse is true for the compressive stress-strain response. Fig. 4 displays the change in instantaneous tensile stiffness (tangent stiffness $E_t$, normalized with respect to the initial stiffness) as a function of the applied strain. It is evident that the “engineering” stiffness drops below zero at a strain of approximately 0.011 while the stiffness in natural space remains positive up to a strain of approximately 0.014.

In the OpenSees implementation of the proposed model, a positive postpeak stiffness is used because softening behavior is observed only in engineering measures of stress and strain. In an effort to replace unrealistic softening behavior at the material level in compression, the Dhakal–Maekawa model is incorporated to represent combined material-geometric effects at the reinforced concrete section level.

References


