Bond Slip Modeling of Reinforced Concrete Columns with Deficient Lap Splices

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SUMMARY:
A novel analytical modeling approach is proposed for simulating the lateral load–deformation response of reinforced concrete columns with deficient lap splices. The modeling approach involves implementing bond stress vs. slip springs in the formulation of a fiber-based macro model. Through this methodology, local bond-slip behavior associated with both pullout failure of reinforcing bars and formation of splitting cracks in concrete can be characterized. The proposed model directly considers the influence of bond slip deformations on the lateral load response of a column under reversed cyclic lateral loading, and successfully represents the distribution of bond stresses and slip deformations, due to either splitting or pullout anchorage failures, along the lap splice region. The analytical model was validated against results of cyclic tests on lap-splice-deficient column specimens; and the model was found to consistently represent the experimental behavior, both at global and local response levels, with a reasonable level of accuracy.

Keywords: reinforced concrete, column, lap splice, bond slip, analytical model

1. INTRODUCTION

Lap splices in reinforced concrete columns in older (pre-1970 construction) buildings, or within some of the non-participating (gravity) frames in relatively new buildings, were typically designed with relatively short lap splice lengths (20 to 24 bar diameters) and moderate transverse reinforcement along the lap splice region. Under earthquake actions, since significant bending moments will develop at the ends of a column, bond slip failures along the splice region may occur at load levels less than that required to reach the nominal or yield moment capacity of the column cross-section; impairing the strength, stiffness, ductility, and hysteretic energy dissipation characteristics of the column during the earthquake. This type of splice-deficient column behavior needs to be well characterized, and accurately represented by reliable analytical modeling approaches, especially within the context of nonlinear analysis procedures for seismic performance assessment of existing buildings. However, the most commonly-used macroscopic modeling approaches for simulating the behavior of columns with lap splices involve defining a zero-length moment vs. slip rotation spring (with predefined unloading and reloading rules) at the location of the lap splice (e.g., Cho and Pincheira, 2006). Although this modeling approach can provide an accurate prediction of the global (lateral load–displacement) response of a column, using predefined unloading/reloading for the rotational bond slip spring introduces incompatibility between flexural deformations (strains) and bond slip deformations, developing in the lap splice region during cyclic loading. Furthermore, since bond slip deformations along the lap splice are assumed to be concentrated at a zero-length rotational spring, this modeling approach is not capable of providing local response and deformation predictions (stresses in strains in concrete and reinforcing steel, slip deformations, or bond stresses) at a particular location on the column, at a particular instant during a generalized loading history.

In this study, a more robust macroscopic model formulation is proposed, for simulating the cyclic bond slip responses of reinforced concrete columns with deficient lap splices or anchorage conditions. This model incorporates constitutive bond slip behavior in the formulation a fiber-based flexural macro-model, which allows distribution and kinematic coupling of flexural and bond slip deformations, and monitoring of local deformations on a column under reversed cyclic loading conditions. Several bond stress vs. slip constitutive relationships can be implemented in the model, depending on the type of reinforcing bar (deformed or plain) used, and possible failure modes (pullout or splitting). The flexible formulation of the model also allows considering the influence of strain penetration effects and the presence of 180-degree hooks, on the lateral load behavior of a column. Correlation studies conducted between model predictions and test results verified that the model can effectively reflect the global response characteristics and failure modes of various column configurations incorporating deficient lap splices or anchorage deficiencies. Overall, the modeling approach proposed is believed to be a significant improvement, towards realistic consideration of bond slip deformations and anchorage failures on the seismic response and performance of reinforced concrete structures.

2. ANALYTICAL MODEL DESCRIPTION

The analytical model presented here is an extension of the so-called Multiple-Vertical-Line-Element Model (MVLEM, Orakcal et al., 2004), which was developed originally to simulate nonlinear flexural responses. In the present model formulation, the coupled axial-flexural and bond slip response of each modified MVLE is represented using a series of uniaxial concrete elements (or concrete macro-fibers), which are connected to rigid beams at the top and bottom levels (enforcing the plane-sections-remain-plane kinematic assumption on concrete). Uniaxial steel elements are connected to the rigid beams (and therefore to concrete), through uniaxial bond slip springs located at top level of each model element. The model element shown in the lower part of Fig. 1(b) (with 18 degrees of freedom) is used along the lap splice region (to represent spliced bars), and the element shown in upper part (with 12 degrees of freedom) is used above the lap splice region of a column. A horizontal spring placed at the center of rotation of each model element (at a relative height *ch*), with a simple nonlinear hysteretic shear force-deformation behavior, simulates the shear response of the model element. In the model formulation, bond slip and flexural modes of deformation are kinematically coupled, whereas shear and flexural modes of deformation are uncoupled. The column is modeled as a stack of *m* model elements, which are placed upon one another, as shown in Fig. 1(a).

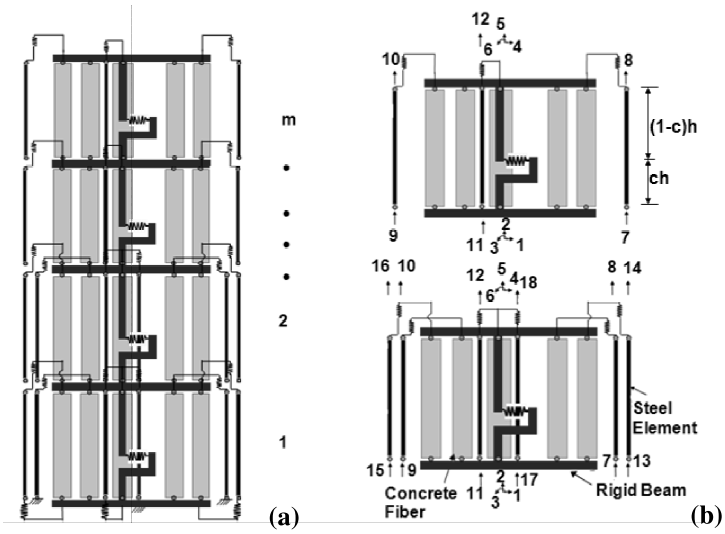

Figure 1. Analytical model: (a) model assembly (b) model elements with degrees of freedom

Refined and state-of-the-art constitutive models are implemented in the model formulation, for describing the cyclic stress-strain behavior of concrete and reinforcing steel. The advanced constitutive relationship proposed by Chang and Mander (1994) (Fig. 2(a)) is implemented in the analytical model for concrete, since it allows details calibration of the monotonic and hysteretic parameters, for improved representation of concrete stress-strain behavior. This constitutive model provides a direct and flexible approach to incorporate important material behavioral features (e.g., hysteretic behavior in tension, progressive gap closure, tension stiffening effects) into the analysis. The constitutive model adopted for reinforcing steel used is the well-known Menegotto and Pinto relationship (Fig. 2(b)), as extended by Filippou et al. (1983) to include isotropic strain hardening effects. The model formulation incorporates cyclic degradation of the curvature of the unloading and reloading curves and thus allows the Bauschinger's effect to be represented. This constitutive model, although simple in formulation, has been shown to accurately simulate experimental behavior.

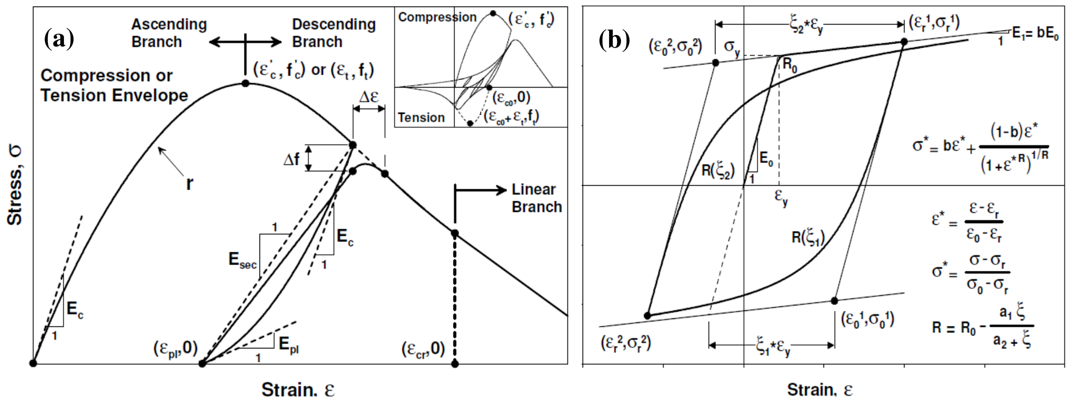

Figure 2. Constitutive material models: (a) concrete (b) reinforcing steel

Advanced constitutive models are also implemented in the model formulation to define the bond stress vs. slip behavior of the bond slip springs (Fig. 3). For deformed (ribbed) reinforcing bars, the bond stress vs. slip model by Harajli (2009) is adopted to represent the splitting-type bond slip behavior expected under inadequate clear cover conditions for unconfined concrete, whereas the constitutive model by Eligehausen et al. (1983) is implemented to represent the pull-out type bond slip behavior expected under adequate clear cover and adequate confinement conditions. For plain (smooth) bars, the bond stress vs. slip constitutive model by Verderame et al. (2009) is used, whereas the bar axial stress vs. hook end slip deformation relationship by Fabbrocino et al. (2004) is adopted to represent the behavior of 180-degree hooks.

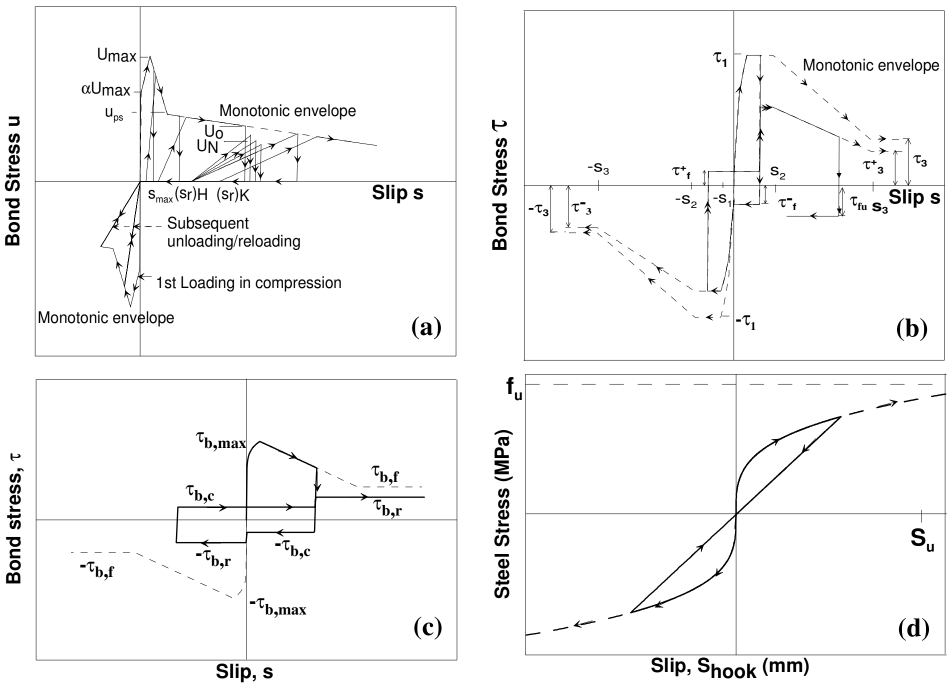

Figure 3. Constitutive models for the bond slip springs: (a) splitting for deformed bars, (b) pull-out for deformed bars, (c) pull-out for plain bars, (d) bar axial stress vs. hook end slip for 180-degree hooks

3. EXPERIMENTAL VERIFICATION OF THE ANALYTICAL MODEL

3.1. Experimental Program by Melek and Wallace (2004)

The six full-scale lap-splice deficient column specimens tested by Melek and Wallace (2004) were first used to calibrate and validate the analytical model. The specimens consisted of a cantilever columns with a foundation blocks attached to a strong floor and loaded laterally at the top, representing the moment distribution (single curvature) along half the height of an interior column in a building. Specimen heights were 1.52, 1.68 and 1.83 meters, and each specimen had 457x457 mm square cross section. Reinforcement configurations, with eight 25 mm nominal diameter vertical bars, and 9.5 mm diameter hoops with 90-degree hooks spaced at 305 mm on center, were based on a review of typical reinforcing details in older buildings (pre-1970 construction) in the United States. A lap splice length of $20d_b$ (20 longitudinal bar diameters) was used in the construction of specimens, corresponding to 60% of the required lap splice length per ACI318-08. The test-day compressive strength of concrete used in the construction of the specimens was approximately 36 MPa, whereas yield strengths of 510 MPa and 480 MPa were measured for the longitudinal and transverse reinforcement, respectively. The axial load levels applied on the specimens correspond to 10%, 20%, and 30% of their axial load capacities. The lateral displacement history imposed during 5 of the 6 tests was fairly typical (standard); consisting of three cycles at each lateral displacement level, with monotonically increasing drift levels of 0.1, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3, 5, 7, and 10%. A lateral displacement history representative of what might be expected in near-fault seismic regions was applied on one specimen (2S20HN). Properties of the test specimens are listed in Table 3.1, whereas Fig. 4 illustrates the reinforcement configuration, lap splice detail, and placement of the strain gauges on the test specimens. The specimens were also instrumented with a large number of displacement transducers for measuring of average flexural, shear, and bond slip deformations, at various locations on each specimen, which allowed comparison of test results with the analytical model predictions also at local (deformation) response levels.

Table 3.1. Test specimen properties, Melek and Wallace (2004)

Specimen	Axial Load P_{ax} ($\% A_g f_c'$)	$l_{o,specimen}/l_{o,ACI318}$	Height (mm)	Lateral Load Protocol
2S10M	10%	0.65	1830	Standard
2S20M	20%	0.65	1830	Standard
2S30M	30%	0.65	1830	Standard
2S20H	20%	0.64	1680	Standard
2S20HN	20%	0.64	1680	Near-Fault
2S30X	30%	0.64	1520	Standard

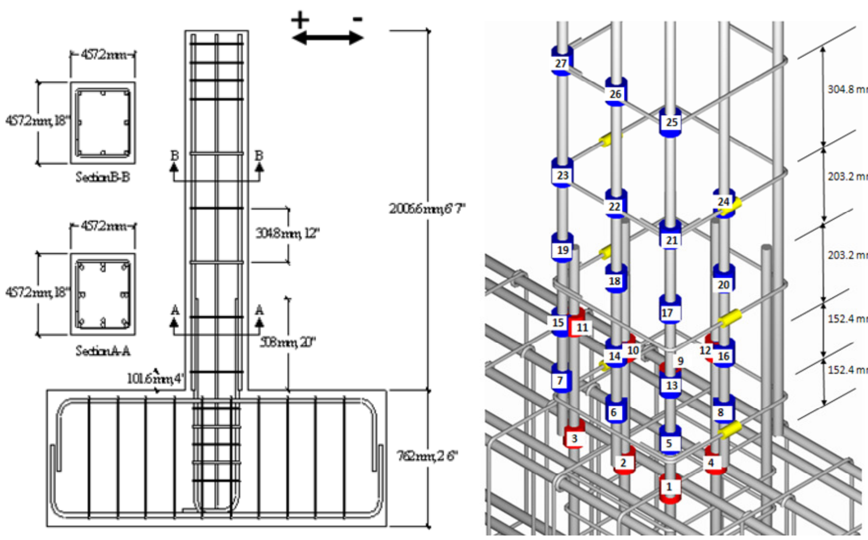

Figure 4. Specimen reinforcement details and strain gauge distribution (Melek and Wallace, 2004)

For detailed comparison of the test results with the analytical model predictions, the model was calibrated to represent measured material properties, as well as the geometry and reinforcement characteristics of the test specimens. 8 model elements were used along the lap splice region of the specimens, where 4 model elements were used above the lap splice region. 26 concrete macro-fibers were used to discretize the cross-section of the specimens. However, it was observed that the model results were not significantly sensitive to the level of discretization, as long as a minimum of 4 model elements were used along the lap splice region and a minimum of 8 concrete macro-fibers were used to define the column cross-section. The monotonic parameters of the constitutive material models were calibrated to represent the results of uniaxial tests conducted on concrete cylinder specimens and rebar coupon samples; whereas the cyclic material parameters were calibrated per the original empirical relationships recommended by Chang and Mander (1994) and Menegotto and Pinto (1973). Both monotonic and cyclic parameters of the bond stress vs. slip relationships used for the bond slip springs were calibrated as defined originally in the constitutive bond slip model formulations by Harajli (2006) and Eligehausen et al. (1983). No adjustment was made on the constitutive parameters to improve the correlation between the test results and the model predictions.

The model formulation, together with the constitutive models, was implemented in MATLAB, together with a displacement-controlled incremental-iterative nonlinear analysis solution strategy, to compare the model results with the experimentally-obtained responses for all of the column specimens tested. Response comparisons were not limited to lateral load vs. top displacement behavior, but also included specimen rotation at different locations, strains in concrete and reinforcing steel, neutral axis depths, and average bond stresses along the lap splice region. Only selected response comparisons are presented here, whereas all of the comparisons are available in the dissertation by Chowdhury (2011).

The experimentally-measured lateral load vs. top displacement responses for column specimens 2S10M, 2S20M, 2S20HN, and 2S30X are compared with the analytical model predictions in Fig. 5. The comparisons indicate that the model provides reasonably accurate load-displacement response predictions, for varying axial load levels and lateral displacement histories. Overall, a good level of agreement is achieved between the test data and model results in terms of column lateral load capacity, lateral stiffness, ductility, shape of the unloading/reloading loops, and pinching characteristics of the response. Furthermore, the behavior characteristics and failure modes observed during the tests, including bond slip initiation (formation and widening of longitudinal splitting cracks), yielding of reinforcement (widening of transverse flexural cracks), and crushing of concrete, were observed to be consistent with the analytically-predicted responses at varying drift levels.

Figure 6 compares the analytically-predicted steel strain histories with measurements of strain gauges No. 11 and 15 (shown in Fig. 5), attached to a starter and longitudinal bar, respectively, for specimen 2S20M. In general, the test measurements and model results show reasonable agreement (considering the typical scatter observed in strain gauge measurements during testing of reinforced concrete members, based on proximity of a strain gauge to a crack), up to a drift level of 1% (data point 450), after which lateral load degradation starts with the initiation of bond deterioration along splice length.

Figure 7 compares the measured and predicted average longitudinal strain profiles (due to flexural deformation of concrete), as well as the neutral axis position (corresponding to zero strain), along the width of specimens 2S10M and 2S20M, under increasing lateral drift levels. The concrete strain profiles shown consider average longitudinal strains over a distance of 330 mm from the column base, and were calculated using measurements from displacement transducers mounted vertically at the base of the column specimens, at peak positive top displacement (top displacement reversal) data points corresponding to selected drift levels. It must be noted that the specimens exhibited sudden lateral load degradation due to splice failure, at drift levels between 1% and 1.5%. Overall, comparisons presented in Fig. 7 indicate that analytical model is capable of providing reasonably accurate predictions of the average concrete strains (both compressive and tensile), rotations (related to the slope of the strain distribution), and the neutral axis depth position measured within the lap splice region of the specimens, particularly for lateral drift levels not exceeding 1.5%. At larger drift levels, together with rapid degradation in lateral load due to splice failure, progressive crushing of concrete was observed at the base of the column specimens, which impaired the accuracy of the model in predicting the measured concrete strain profiles (Chowdhury, 2011).

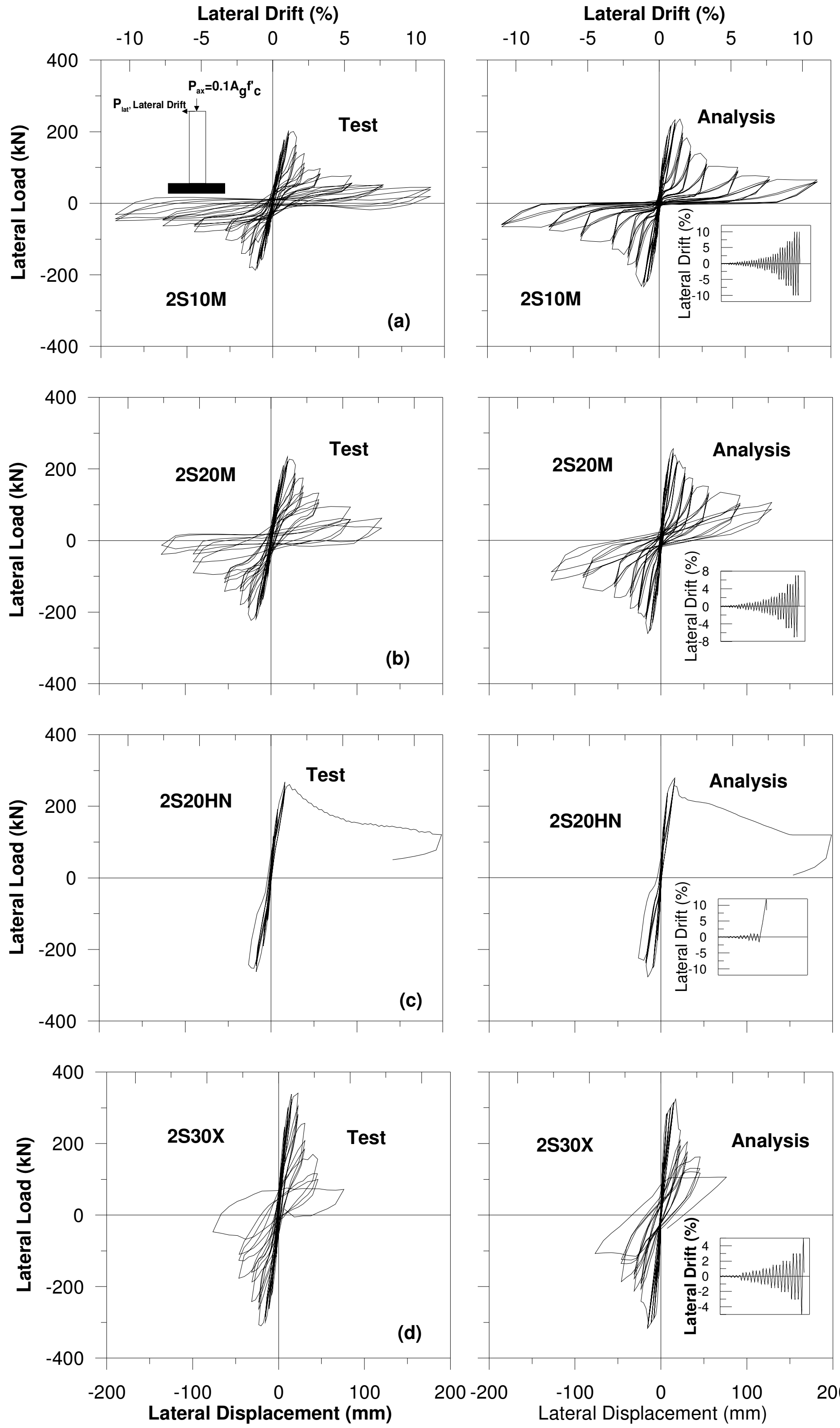

Figure 5. Comparison of measured and predicted lateral load vs. top displacement responses: (a) Specimen 2S10M, (b) Specimen 2S20M, (c) Specimen 2S20HN, (d) Specimen 2S30X

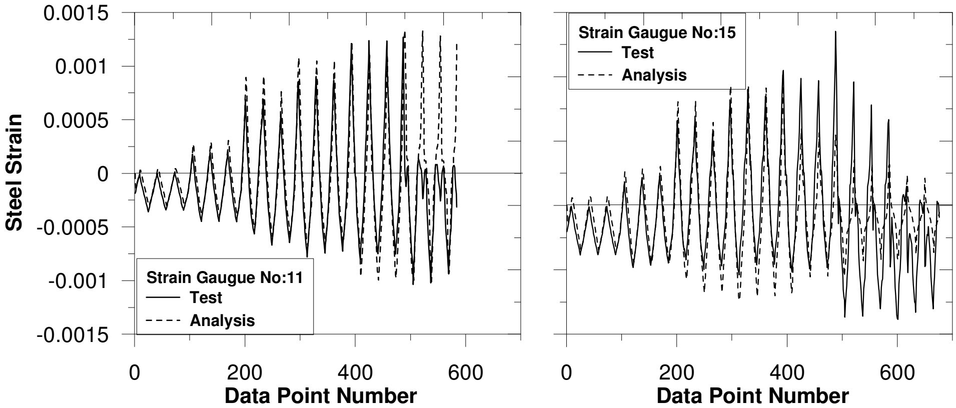

Figure 6. Comparison of measured and predicted steel strain histories for Specimen 2S20M

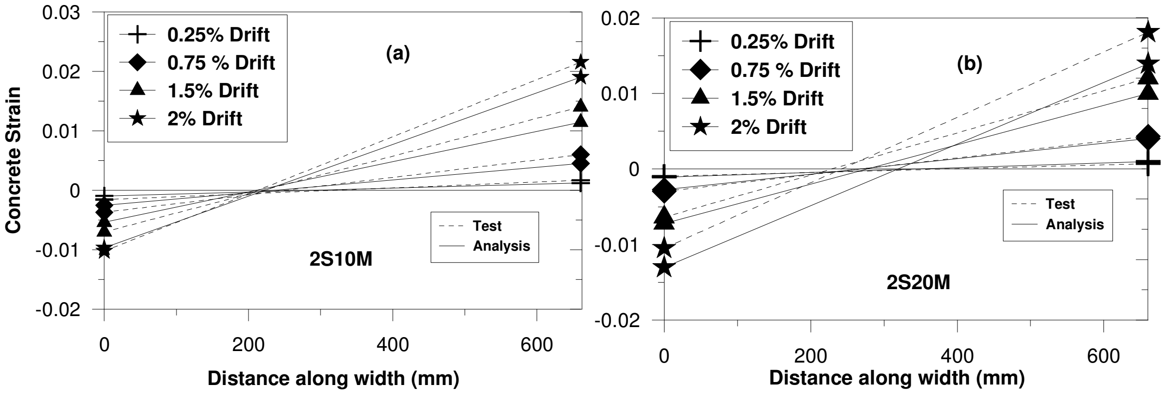

Figure 7. Comparison of measured and predicted average concrete strain profiles in lap splice region: (a) Specimen 2S10M, (b) Specimen 2S20M

3.2. Other Experimental Studies in the Literature

For further experimental verification of the model, analysis results were compared with numerous test results presented in the literature on columns with various configurations. Results of 30 cyclic loading tests conducted by 11 research groups were used for the comparisons. The column specimens investigated had varying geometries, material strengths, and reinforcement details; and were tested under various axial load levels. Results for only four column specimens are presented here to demonstrate the effectiveness of the model in predicting distinct response characteristics (strain penetration effects, bond-slip-governed responses, coupled-flexural-and-bond-slip responses, responses of columns with smooth bars and hooks), whereas response comparisons for all 30 tests are available in the dissertation by Chowdhury (2011).

In order to investigate the influence of bond slip deformations within the reinforcement anchorage region (i.e., specimen pedestal) on the response (the so-called "strain penetration effects"), test results presented by Low and Moehle (1987) on a column specimen with continuous longitudinal reinforcement was used. Two column specimens, one tested by Aboutaha et al. (1996) and one by Harajli and Dagher (2008) were included in the comparisons for investigating the variation in the lap splice length on the column response, as well as to demonstrate the model performance in predicting bond-slip-governed versus coupled-flexural-and-bond-slip responses. The specimen tested by Verderame et al. (2008) was used to validate the model for lap-spliced columns incorporating plain (smooth) reinforcing bars and 180-degree hooks.

Important properties of the column specimens are presented in Table 3.2, whereas Fig. 8 illustrates the dimensions and reinforcement characteristics for three of the specimens investigated.

Table 3.2. Test specimen properties

Researcher	Specimen	Dimensions			Longitudinal Reinf.			Transverse Reinf.	Concrete f'_c (Mpa)	Axial Load ($\%A_g f'_c$)
		b (mm)	h (mm)	l (mm)	Amount	l_s* (mm)	f_y (MPa)			
Low-Moehle	Specimen 1	127	165	692	6-ϕ6 & 4-ϕ10	178 ($18d_b$)**	450	ϕ13 @ 129mm	36	5%
Aboutaha	FC15	686	457	2743	8-ϕ25	610 ($24d_b$)*	434	ϕ10 @ 407mm	28	0
Harajli and Dagher	C16	400	200	1400	8-ϕ16	480 ($30d_b$)*	528	ϕ8 @ 200mm	40	0
Verderame	C540A1	300	300	1570	6-ϕ12	480 ($40d_b$)*	355	ϕ8 @ 100mm	25	24%

* Lap splice length

** Embedment length within pedestal

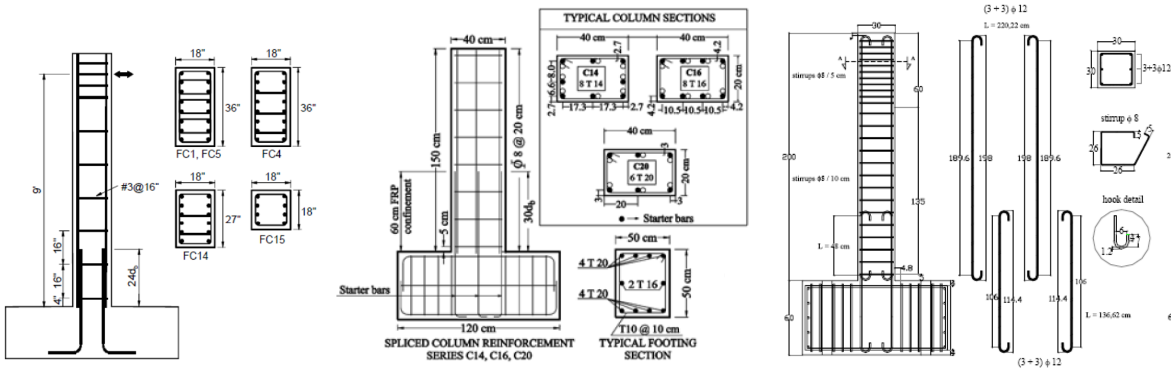

Figure 8. Column specimen details: (a) Specimen FC15, Aboutaha et al. (1996), (b) Specimen C16, Harajli and Dagher (2008), (c) Specimen C540A1, Verderame et al. (2008)

Experimentally-measured lateral load vs. top displacement responses were compared with the analytical model predictions in Fig. 9, for the four column specimens considered. The comparisons indicate overall, that the model provides reasonable accurate predictions of the experimental responses, for columns with various configurations and response characteristics. Analytically-obtained responses are in good agreement with the test results; in terms of failure modes, lateral load capacity, stiffness, ductility, pinching attributes, and hysteretic energy dissipation capacities.

The model can successfully capture the influence of bond slip deformations within the anchorage region on the stiffness degradation characteristics of the cyclic response of a column (the so-called “strain penetration effects”), as shown in Fig. 9(a). Figure 9(b) demonstrates the effectiveness of the model in predicting bond-slip-dominated responses, as was observed previously for the specimens tested by Melek and Wallace (2004). Figure 9(c) illustrates that the model prediction is also reasonably accurate for a specimen experiencing a combined failure mode consisting of coupled bond slip and flexural responses. The specimen tested by Harajli and Dagher (2008) experienced flexural yielding of the longitudinal reinforcement together with bond slip failure along the lap splice, which is captured by the analytical model, as shown in Fig. 9(c).

The analytical model is also found to capture the lateral load capacity and overall response characteristics of the column specimen tested by Verderame et al. (2008), which incorporates plain (smooth) reinforcing bars and 180-degree hooks. However, the model fails to provide accurate predictions of the pinching attributes of the response of the specimen (Fig. 9(d)). For such columns, the discrepancies in the analytical model predictions may be recovered upon implementing realistic hysteretic rules in the bar stress vs. hook end constitutive model for 180-degree hooks, as opposed to the origin-oriented hysteresis loops used in this study (Fig. 3(d)). A hysteretic bar stress vs. hook end constitutive model is presently not available in the literature.

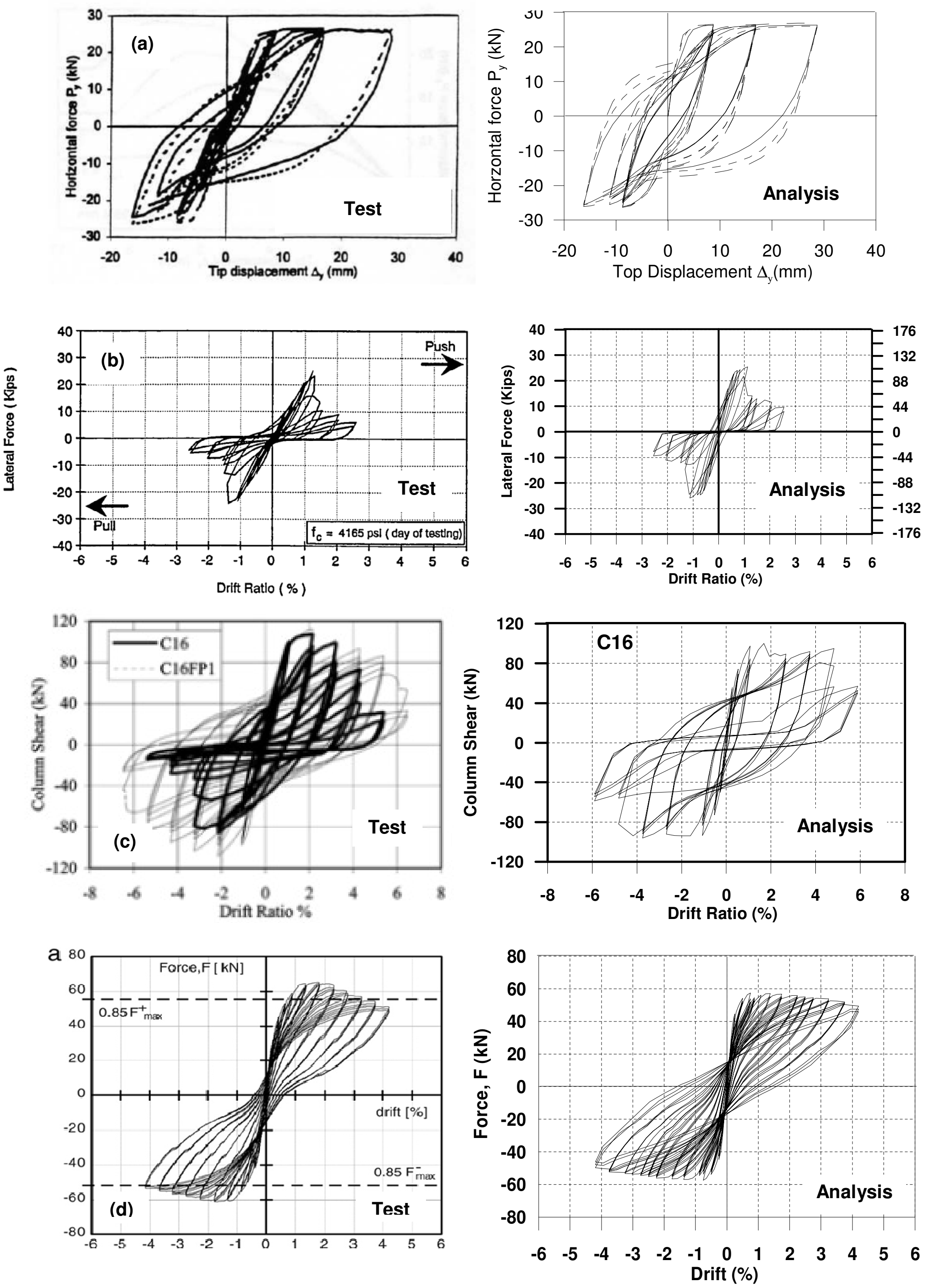

Figure 9. Comparison of measured and predicted lateral load vs. top displacement responses: (a) Specimen 1, Low and Moehle (1987), (b) Specimen FC15, Aboutaha et al. (1996), (c) Specimen C16, Harajli and Dagher (2008), (d) Specimen C540A1, Verderame et al. (2008)

4. CONCLUSIONS

A relatively simple yet robust macroscopic model formulation was proposed, for simulating the cyclic bond slip responses of reinforced concrete columns with deficient lap splices. The proposed model incorporates constitutive bond slip behavior in a fiber-based flexural macro-model, which allows coupling of flexural and distributed bond slip deformations under reversed cyclic loading conditions. Several constitutive bond slip relationships were implemented in the model formulation, depending on the type of reinforcing bar (deformed or plain) used, and the failure mode (pullout or splitting) expected. The flexible formulation of the model also allows investigating the influence of strain penetration effects, use of plain bars, and the presence of 180-degree hooks, on the lateral load behavior of a column.

The model was shown to effectively reflect the global response characteristics and failure modes of various column configurations incorporating deficient lap splices or anchorage deficiencies. The model provided reasonably accurate predictions for important response attributes, including lateral load capacity, degradation in lateral load due to bond slip failure, ductility, cyclic stiffness characteristics, pinching properties, and strain penetration effects. Local response and deformation predictions of the model (steel strains, concrete strain profiles, rotations, and neutral axis position) were also representative of the experimental measurements, with a reasonable level of accuracy. The model is believed to be promising towards obtaining improved seismic response predictions for reinforced concrete buildings with splice-deficient columns, which is important for the application of performance-based evaluation methods for existing structures.

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