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Finite Element Simulation of Steel Plate Concrete Beams subjected to Shear

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Abstract

In a test series ofSteel plate Concrete (SC) beams conducted by the authorsto determine the minimum shear reinforcement ratio, complex structural behavior of the tested beams was observed, including shear cracking occurred within the concrete in the web and bond-slip failure of the bottom steel plate of the beam due to insufficient shear reinforcement ratio (Qin et al. 2015).This paper focuses on finite element simulation (FEM) of the SC beams withemphasis on shear and bond-slip behavior. A new constitutive model is proposed to account for the bond-slip behavior of steel plates. Also, the Cyclic Softened Membrane Model proposed by Hsu and Mo (2010)is utilized to simulate the shear behavior of concrete with embedded shear reinforcement. Both constitutive models areimplemented into a finite element analysis program based on the framework of OpenSees (2013).The proposed FEM is able to capturethe behavior of the tested SC beams.

I. Introduction

In recent years, steel plate concrete (SC) has been widely used for building as well as nuclear containment structures to resist lateral forces induced by heavy winds and severe earthquakes.Compared to the conventional reinforced concrete, SC has higher strength and ductility, enhanced stiffness, and large energy dissipation capacity. SC also experiences faster construction and cost-effectiveness because steel plates can serve as formwork for concrete during construction.SC is a composite structure system thatconsists of two layers of relatively thin steel plates and a sandwiched concrete layer. In the composite structure system, two ends of each shear connector (cross tie)are welded on steel plates to connect the steel plates and the concrete. Similar to the Bi-Steel constructiondeveloped by British Steel, SC overcomes some of the on-site construction problems of the steel-concrete-steel sandwich constructionthatuses shear studs(Bowerman and Chapman 2000).The sandwich construction using shear studs would have been difficult(Bowerman et al. 2002).SCcomposite structure system, however, acts in a similar way to doublyReinforced Concrete (RC).Compared to the conventional constructionforms,SC is a strong and efficientstructure type with a great deal of important advantages(Braverman et al. 1997; Mizuno et al. 2005; Kim et al. 2007; Yan 2012).Theoretically, as long as the integrity of the SC structure is sustained, the SC structure can take the full advantage of respective strengths of steel and concrete.SC structures are widely applicable in structural engineering practice, i.e. the containment wall for nuclear power plants (Yamamoto et al. 2012),the liquid and gas containment structures and the military shelters, etc. (Zhang 2009; Yan et al. 2015).In recently developed nuclear power AP1000 plants (NPPs), SChas been

used forthe shield building and internal structures.
Considerable out-of-plane shear force is a unique load patternforSC structures.For instance, SC nuclear containments (Fig. 1) are subjected to out-of-plane shear at the regions close to the foundation and at the connections or interfaces with other structures (Oesterle and Russell 1982; Walther 1990).Forthe shear failure of RC and PC members, ACI 318 Code(2011)gives limit on shear reinforcement to ensure a ductile failure mode.For the design of SC members in current AP1000NPPs, ACI 349 Code(2006), which adoptsACI 318 Code directly, isused.However, the applicability of ACI 349 Code to SC membersneeds to be further investigated.It is of essential importanceforSC memberssto precludebrittle shear failure in designand to develop rational methodin analysis.Based on tests on SC beams by the authors,the minimum amount of shear reinforcement (cross ties) to ensure theductile behavior and the method to evaluate shear strength were recommended for the shear design of SC members.However, a rational finite element simulation to analyze SC members is needed with consideration of shear and bond-slipbehavior.

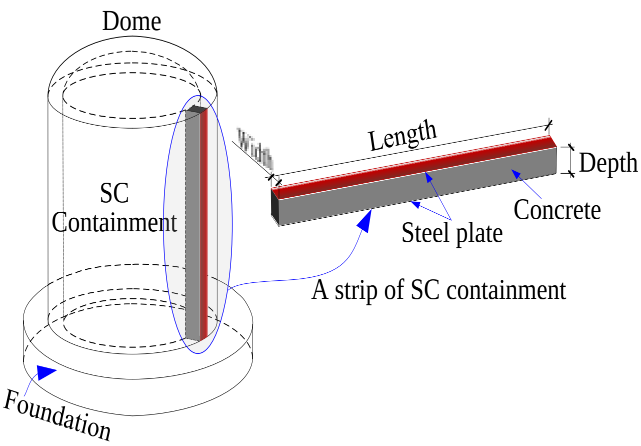


Fig. 1SC nuclear containment and a cut strip

Experimental investigations have shown that the stiffness of SC composite structure systemis largely dependent upon the efficiency of the shear connectors that connect the steel plates to the concrete(Wright and Oduyemi 1991; Roberts et al. 1996; Coyle 2001; Xie et al. 2007). The SC composite system is as rigidas an equivalent doubly Reinforced Concrete (RC)on the condition that theshear connectorsare fully rigid and the steel plates cannot move relatively to the concrete.However,the stiffness of the shear connectors is always limited, therefore, the longitudinal shear generated at the interface between the steel plate and the concrete leads tothe bond-slip between them.The bond-slip behavior has a significant influence on behavior of SC members, such asstiffness,deflection, strength and failure mode, etc. (Coyle 2001; Foundoukos 2005; Subramani et al. 2014; Nama et al. 2015). Pronounced bond-slip betweenthe bottom steel plate and the concrete was observed in the series of tests conducted by the authors.

In the analysis of Steel-Concrete-Steel sandwich beams with overlapped headed shear studs,Roberts et al.(1996) proposed an approximate method to consider the influence of bond-slip.This approximate method was used in the simplified Finite Element Models (FEMs) for the analysis of double skin composite (DSC)slabs (Shanmugam et al. 2002). In these simplified FEMs, the overlapped headed shearstuds were assumed to resist the transverse shear, whichweremodeled indirectly by adjusting the shear stress parameters of the concrete.This simplification significantly reduced the difficulty of modeling, and the total amount of elementswasreduced as well.A tapering web truss model for the analysis of Bi-Steel beams was proposed by Xie et al. (2007), in which an analytical methodwas proposed to calculate the deflection of Bi-Steel beamswith the influence ofbond-slip.The truss modelhad two assumptions: (1) the steel and concrete wereelastic and the concrete had no tensile strength; (2) shear deformation was neglected. In the study of static behavior of Bi-steel beams, two-dimensional FEMswere developed by Foundoukos(2005),in whichtwo-dimensional solid plane stress elements were used. Because the elastic concrete compression behavior was used, the effect of concrete shear failure could not be rationally studied. In the analysis of DSC beams with J-hook connectors, three-dimensional FEMs using ABAQUS were proposed by Yan(2014), in which the interaction between the steel plate and the concrete was considered by defining a "hard contact" formulation and "penalty friction" formulation. These three-dimensional FEMs provided good agreements on the ultimate strength and nonlinear load-deflection behavior of tested beams,and the complex geometry of the J-hook connectors could be considered.However, complexparameters were needed to define materials in the three-dimensional FEMs.

For the purpose of this study, OpenSees (2013), an object-oriented programming framework for simulation of earthquake engineering research is chosen as finite element framework to develop the analysis program. OpenSees, which stands for Open System for Earthquake Engineering Simulation, was developed in the Pacific Earthquake Engineering Center (PEER). It is an open-source framework that allows researchers to implement their proposed material model. The source code is openly available to the structural engineering research community to evaluate and modify. Using OpenSees framework, Mo et al. (2005) successfully implemented the material modelsdeveloped by the University of Houston research group for predicting the behavior of reinforced concrete into a finite element analysis program called Simulation of Concrete Structure (SCS). In this paper, the SCS program will be extended by adding a new proposed model for bond-slipped steel plates to predict the structural behavior of the tested SC beams.

II. Experimental Program

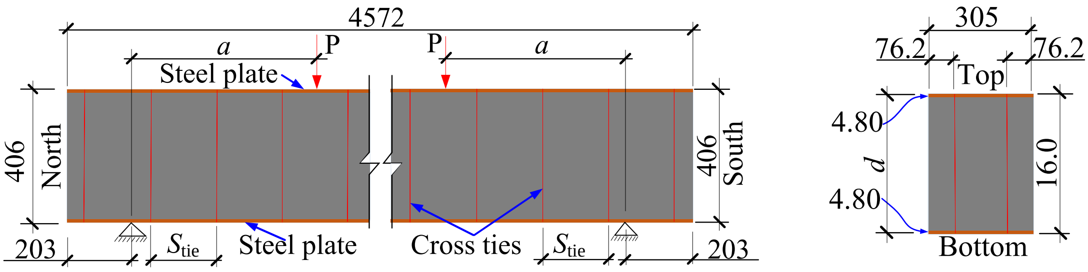
2.1 Specimens

Six SC beams (SC1 to SC6) have been tested at Thomas T. C. Hsu structural research laboratory, the University of Houston.The geometric properties of the SC beams are shown inFig. 2. The length L, width$w$, and depth$d$ of each SC beamwere4572 mm (180 in.), 305 mm (12.0 in.), and 406 mm (16.0 in.), respectively. The top and bottom steel plates hadthe same thickness t of 4.80 mm (3/16 in.), and the diameter of cross ties $\emptyset$ was6.30 mm (1/4 in.).Fig. 2shows the dimensions of the specimens studied in this paper.To fully secure the connections between steel plates and cross ties, penetration welding was applied.As shown inFig. 3,the welding was applied on both outside and inside surfaces of steel plates.

Theshear span-to-depth (a/d) ratio was a main parameter. The shear span a, as shown inFig. 2a, wasdefined as the distance from the center line of the support to the center line of loading point.The depth d, as shown inFig. 2b, wasdefined as the distance from the extreme top fiber to the center line of the bottom steel plate.Based on the experimental studies on RC members by Kani(1964) and on PC members by Laskar et al. (2010), two shear span-to-depth (a/d) ratios, 1.5 and 2.5, were used as two typical shear governing cases for the SC beams.

The other main test parameterwastheshear reinforcement (cross ties) ratio ρ_{sv}.The tests show that more shear reinforcement is required for SC beams tested under the condition ofa/d=2.5 than what for SC beams tested under the condition ofa/d=1.5. The similar trend was also found in RC members by Kuo et al.(2014) and in PC members by Laskar et al. (2010).

In this paper, four specimens, SC3, SC4, SC5 and SC6, were selected to validate simulation method considering effects of shear and bond-slip behavior.



(a) Elevation dimentionsof SC beams Cross setion dimensions

Fig. 2Dimensions of SC beams (unit: mm)

2.2 Material Properties

Concrete compressive strength (f_c') varied from 40.1 to 55.2 MPa (5.80 to 8.00 ksi), as shown inTable 1. Deformed No. 2 reinforcing bars (Ø = 6.30 mm) were used as the cross ties, and high-strength low-alloy structural steel (ASTM A572-50) was used as the top and bottom steel plates. The yield strength of cross ties (f_{yv}) and yield strength of steel plates (f_y) were 419 MPa (60.8 ksi) and 379 MPa (55.0 ksi), respectively.

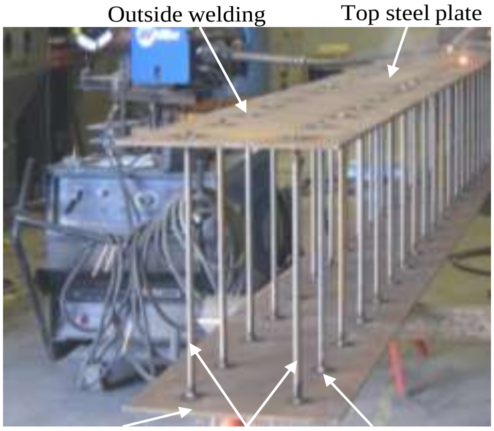
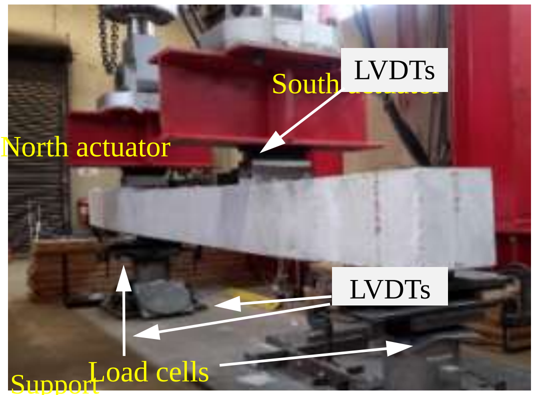


Fig. 3Penetration welding of shear reinforcement (cross ties)

2.3 Test Setup and Loading Procedure

The specimens were subjected to vertical loading provided by north and/or south actuators with a capacity of 600 kips (2670 kN) each, as illustrated in Fig. 4a. The loads and displacements of the actuators were controlled by the MTS Flex system. The loading protocol was comprised of several loading steps. Every loading step had a constant loading rate of 2.54 mm (0.10 in.) per 15.0 minutes. During each loading step, the loading might be put on hold and resumed, to check and mark the cracks. Load cells installed under supports were used to measure shear forces in each specimen. Linear Variable Differential Transformers (LVDTs) were used to measure deflection of each specimen, as shown inFig. 4b.



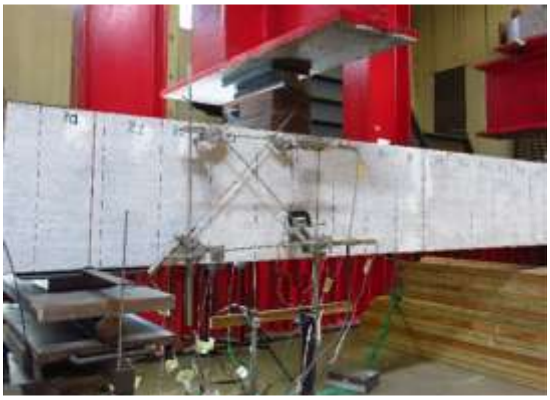


Fig. 4Test setup of specimen

2.4 Crack Patterns

Within shear spanofeach specimen, inclined shear cracks and pronouncedbond-slip occurred.For all the specimens, bond-slip existed only in the bottom interface from the side of beam to the shear crack, no bond-slip behavior wasobserved in other part of bottom interface or in any part of top interface, which agreed with previous test observations on similar structural members by Shanmugam et al. (2002)andXie et al. (2007).

Taking SC4 north for instance, crack patterns of shear and bond-slip are shown in Fig. 5a. The direction of upper part of the shear crack was approximately45˚, which wasa typical symbol of shear crack. Bond-slip deformation in bottom interface was approximately 19.0 mm (0.75 in.), as shown inFig. 5b, and bond-slip only existedfromthe left side of the beam to the shear crack, as shown in Fig. 5c.

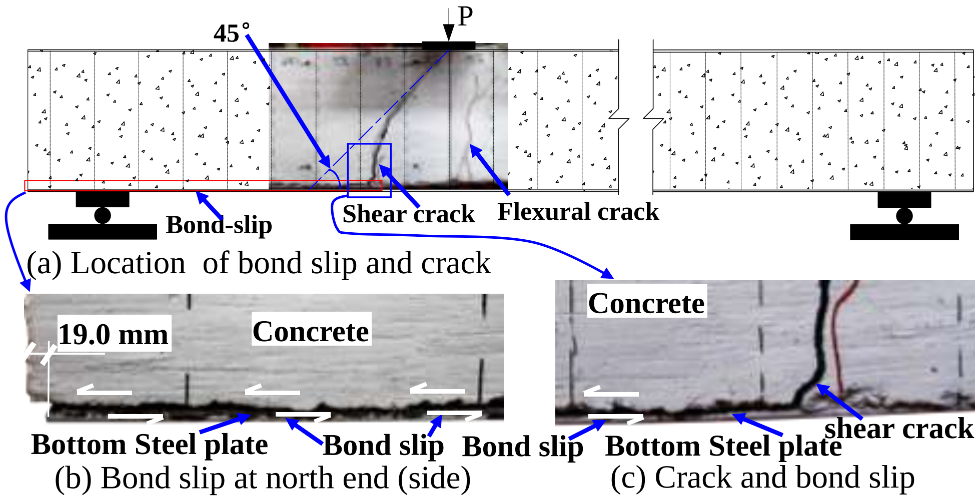


Fig. 5Crack patterns in SC4 north

III. Material Models forFEM

3.1 CSMM Model for Concrete with Embedded Cross Ties

The web of the SC beam,which is comprised of concrete and embedded cross ties, can be treated as regular reinforced concrete structures. To analyze the shear behavior of RC structures, Cyclic Softened Membrane Model (CSMM) proposed by Mansour and Hsu (2005a; 2005b) can be used. The model is capable of accurately predicting the pinching effect, the shear ductility and the energy dissipation capacities of RC members (Hsu and Mo, 2010).CSMM included the cyclic uniaxial constitutive relationships of concrete and embedded mild steel. The characteristics of these concrete constitutive laws include: (1) the softening effect on the concrete in compression due to the tensile strain in the perpendicular direction; (2) the softening effect on the concrete in compression under reversed cyclic loading; (3) the opening and closing of cracks, which are taken into account in the unloading and reloading stages, as shown inFig. 6. The characteristic ofembedded mild steel bars include: (1) the smeared yield stress is lower than the yield stress of bare steel bars and the hardening ratio of steel bars after yielding is calculated from the steel ratio, steel strength and concrete strength; (2) the unloading and reloading stress-strain curves of embedded steel bars take into account the Bauschinger effect, as shown inFig. 7.

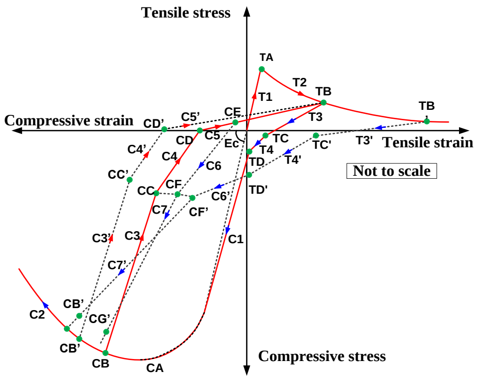


Fig. 6Envelop of stress-strain curve of concrete

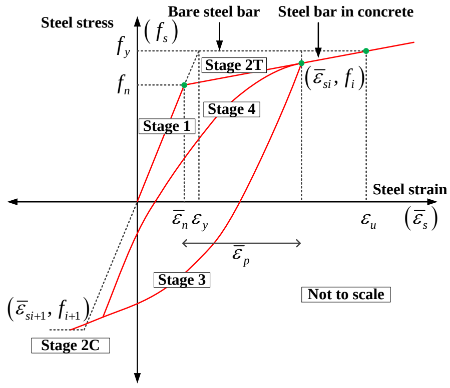


Fig. 7Envelope of stress-strain curve of shear reinforcement (cross ties)

3.2 Bond Slip-basedConstitutive Model for Steel Plates

3.2.1 Stress-strain Characteristic

The experimental results show that the tested SC beams hadabond-slipcharacteristic before reaching its flexural or shear capacities. In other words, the bond between concrete and steel plate was not sufficient to transfer the stress in the steel plate to concrete in SC beams. Therefore, the constitutive model of the typical mild steel cannot be used for the steel plate in FE analysis.

In this study, a new constitutive model for steel plate, called bondslip-basedmodel, is proposed. Due to the bond slip, the model will take into account the reduction of both the nominal yield stress and the elastic modulus. The stress and strain curve for the bondslip-based model, shown inFig. 8, is comprised of three parts: (1) The linear elastic part up toyield stressf_{yslip} , which is smaller than the yielding stress of the typical mild steel;(2) the plastic part at which the steel plate continues to deform under constant load up to a strain of three times the strain at yielding; (3) the descending region at which the bond between the steel plate and concrete has been weakened and the member would fail. The negative slope of the curve in this part is proposed to capture the descending portion of the load-deflection curve of SC structures.It is assumed that the stress would drop to 20% of the peak to avoid any convergence problems in the finite element analysis.

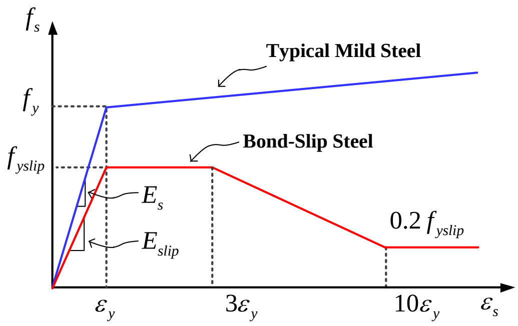


Fig. 8 Stress-strain relationship of the bondslip-based steel model

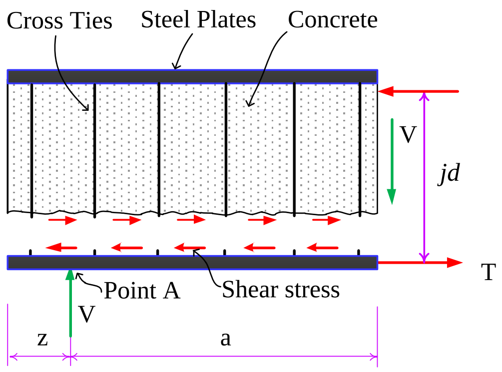


Fig. 9 Free-body diagram of SC beam

To determine the yield stress of the bondslipped steel, f_{yslip} , a free body diagram is considered which shows all the forces on the beam between the point of application of the load and the end of the beam, as shown inFig. 9. As it can be seen from the figure, the shear transfer in the case of steel-plate concrete structures happens across a plane at the interface of steel plate and concrete. Therefore, a shearfriction model should be used to find the relationship between the sheartransfer strength and the reinforcement crossing the shear plane. An equation fromACI 318-11 provision,which is used to estimate the sheartransfer strength of reinforced concrete when the shear reinforcement is perpendicular to the shear plane, can be adopted to determine the shearfriction strength between concrete and steel plate, in which the nominal shear strength V_n is given by

$$V_n = 0.8 A_{sv} f_{yv} + A_c K_1 \quad (1)$$

where A_c is the area of concrete section resisting shear transfer, A_{sv} is the area of cross ties within the transfer length, f_{yv} is the yield strength of the cross ties. K_1 is the maximum bond stress between concrete and steel plate.

Eq. (1) can also be written as

$$V_n = b\left(z+a\right)\left(0.8\rho_{sv} f_{yv} + K_1\right) \quad (2)$$

where b is the beam width, a is the shear span, z is the distance from the center of the support to the end of the beam, ρ_{sv} is the percentage of cross ties within the transfer length.

In the right side of Eq. (1), the first term represents the contribution of cross ties to sheartransfer resistance. The coefficient 0.8 represents the coefficient of friction. The second term characterizes the sum of the resistance provided by friction between the rough surfaces of concrete and steel plate and the dowel action of the cross ties (ACI 318-11).

To maintain equilibrium condition, the nominal shear strength given in Eq. (1) needs to be balancedby the total tensile strength of the bottom steel plate, which can be expressed as

$$T_{\max} = f_{yv} A_{sb} \quad (3)$$

where $A_{sb} = bt$ is the total area of the bottom steel plate, t is the thickness of the steel plate.

Based on Eq. (2) and Eq. (3), the yield stress of the bondslip-based steel can be determined and expressed by Eq. (4).

$$f_{yslip} = \frac{\left(z+a\right)}{t}\left(0.8\rho_{sv} f_{yv} + K_1\right) \;\; \leq \;\; f_y \quad (4)$$

Using ε_y as the yield strain, the modulus of elasticity for bondslip-based steel can becalculated by Eq. (5), which is already taken into account the reduced stiffness due to bondslip.

$$E_{slip} = \frac{f_{yslip}}{\varepsilon_y} \quad (5)$$

3.2.2 Maximum Bond Stress between Concrete and Steel Plate

As it can be seen from Eq.(4), to determine the yield stress of the bondslip-based steel, the maximum bond stress between concrete and steel plate, K_1, needs to be specified. From the test results, itwas observed that the maximum bond stress between concrete and steel plate was affected by the a/d ratio, the amount of cross tie and the strength of concrete.In this study,the value of K_1 is calibrated using regression analysis.

Taking a moment equilibrium at point A in the free-body diagram (Fig. 9) and using the effective depth $jd = 0.9d$ (AASHTO, 2010), the maximum bond stress between concrete and steel plate can be written as:

$$K_1 = \frac{V_{\max} a}{0.9db\left(z+a\right)} - 0.8\rho_{sv} f_y \quad (6)$$

where V_{max} is the peak shear force obtained from the test results.

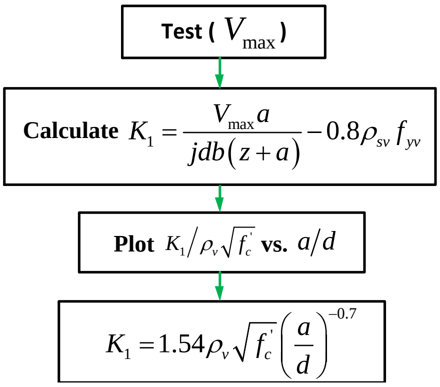


Fig. 10Flowchart for K_1calibration

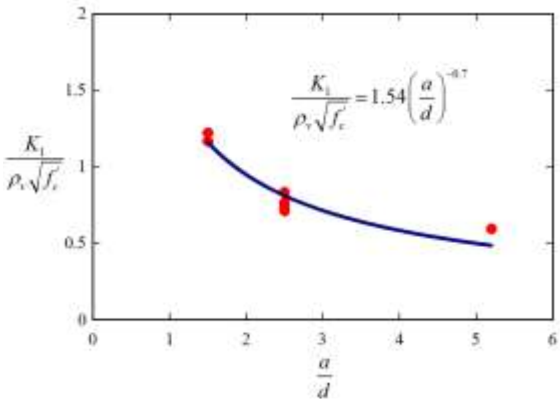


Fig. 11$K_1$and a/d relationship of SC beams

Table 1 shows the calculation results of K_1 for the tested SC beams with normal concrete. The procedure to find an expression for K_1 is simplified in a flowchart shown in Fig. 10.The value of K_1 is normalized with the percentage of cross ties and the square root of concrete strength and plotted against a/d ratio in order to perform regression analysis for finding the relationship between the normalized value ofK_1 and the a/d ratio, as illustrated inFig. 11.

After performing the regression analysis, the expression for K_1 for SC beams with normal concrete is found to be:

$$K_1 = 1.54\rho_{sv}\sqrt{f_c'}\left(\frac{a}{d}\right)^{-0.7} \tag{7}$$

Table 1 Calculation of K_1 for the tested SC beams

Specimen	b (mm)	t (mm)	a/d	ρ_{sv} (%)	f_{yv} (MPa)	f'_c (Mpa)	jd (mm)	V_{max} (kN)	K_1 (MPa)
SC1 North	305	4.763	2.5	0.102	413	56	402	121.71	0.584
SC1 South	305	4.763	2.5	0.102	413	56	402	116.37	0.543
SC3 North	305	4.763	2.5	0.137	413	40	402	155.35	0.722
SC3 South	305	4.763	2.5	0.137	413	40	402	143.45	0.632
SC4 North	305	4.763	2.5	0.164	413	51	402	190.04	0.896
SC4 South	305	4.763	2.5	0.205	413	51	402	235.69	1.105
SC5 South	305	4.763	1.5	0.137	413	55	402	248.77	1.241
SC5 North	305	4.763	1.5	0.164	413	55	402	287.99	1.419
SC6	305	4.763	5.2	0.137	413	55	402	127.58	0.604

IV. Implementation Models to SCS

The implementation of the proposed models into OpenSees framework is shown in Fig. 12. The CSMM modelwas implemented by Mo et al. (2008). The model includes two uniaxial material classes, ConcreteZ01 and SteelZ01, and one NDMaterial class, RCPlaneStress. The ND material is related with SteelZ01, ConcreteZ01 to determine the tangent material constitutive matrix and to calculate the stress of the quadrilateral element that is used for modeling of concrete and cross ties.

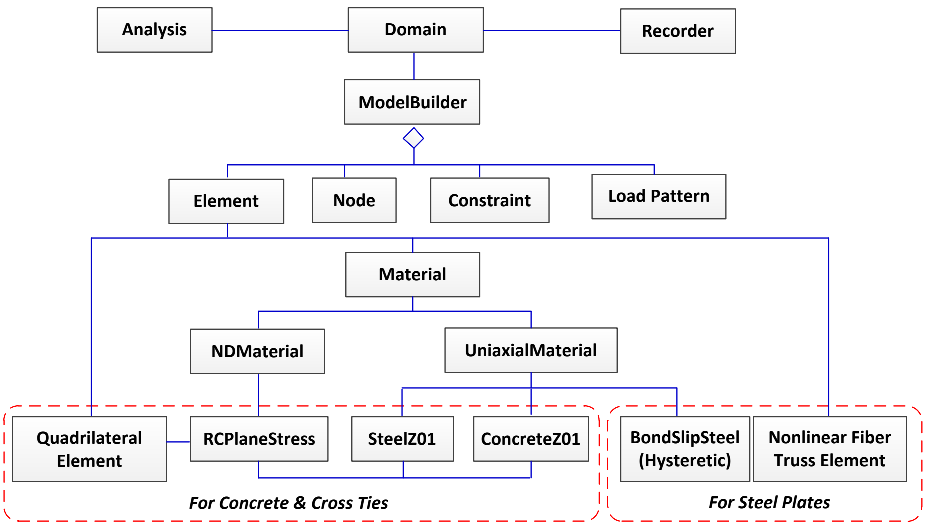
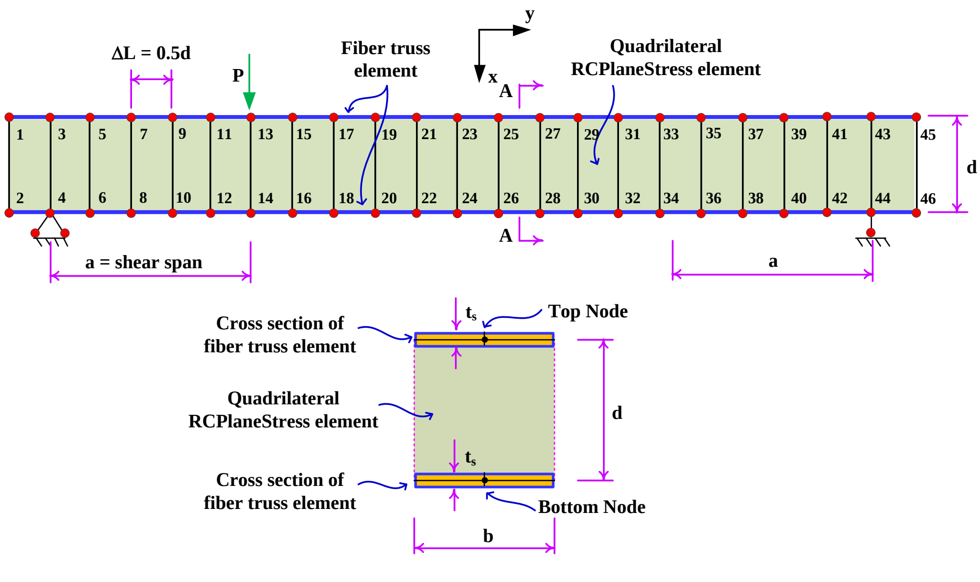


Fig. 12Implementation of the proposed models in OpenSees

Additionally, a new uniaxial material class, so-called BondSlipSteelK01, which is based on the proposed bondslip-based steel model, is implemented for modeling of steel plates, as shown in Fig. 12. The new material class is developed by modifying the envelope curve of Hysteretic material class available in OpenSees. For each trial displacement increment in the analysis procedure, BondSlipSteel will receive the strain from the nonlinear fiber truss element, determine the tangent material matrix and calculate the stress of the element based on the stress-strain curve of the proposed bondslip-based steel model (Fig. 8). The tangent material matrix is used to formulate the element stiffness matrix, and the stress is used to compute the force resistance of the truss element.

V. Finite Element Simulation

Finite element analyses were conducted on the tested SC beams. The finite element mesh and the boundary condition of each beam are shown in Fig. 13. The top and bottom flanges of the beam, which included steel plates, were modeled using total 44 2-node nonlinear truss elements with fiber section. Because the truss element only resisted tensile and compressive forces, the mesh of 2x2 for fiber section was sufficient to capture the structural response of the steel plates. The web of the beam, which was comprised of concrete and cross ties, was simulated using total 22 4-node quadrilateral elements. RCPlaneStress and BondSlipSteel materials were assigned to the quadrilateral and truss elements, respectively. The applied load was applied to one or two nodes in the top flange of the beam. The location of the applied load depends on the configuration of the test setup of each specimen.



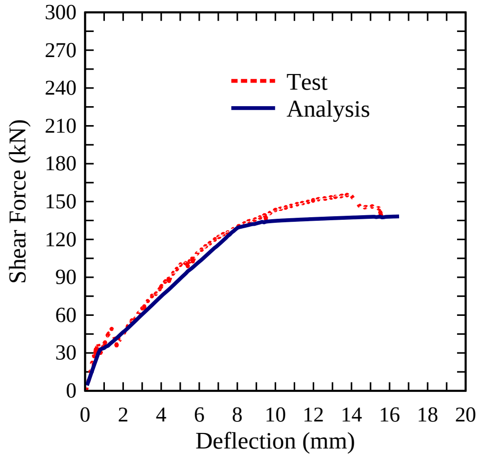
Cross Section A-A

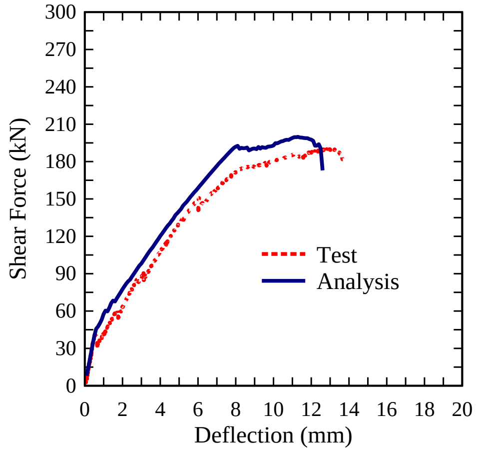
Fig. 13Finite element meshof SC beams

The analyses were performed monotonically by displacement control schemes. The vertical loads were applied by the predetermined displacement control on the vertical displacement of the referenced node located under the load. The common displacement increment used in the analyses was 0.5 mm. Convergence was obtained quite smoothly during the monotonic analyses. The modified Newton-Raphson method was used as the solution algorithm. The nodal displacement and corresponding vertical forces were recorded at each converged displacement step, and the stress and strain of the elements were also monitored.

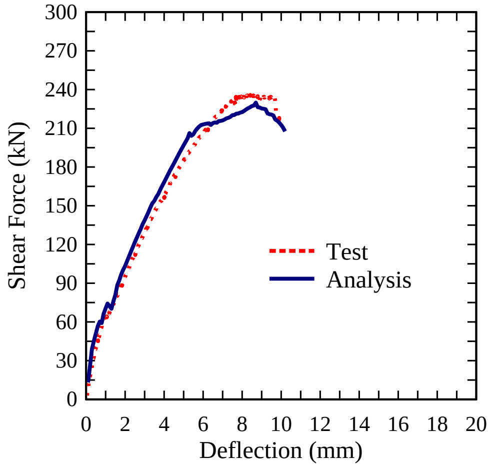
VI. Validation of Proposed Models for SC beams

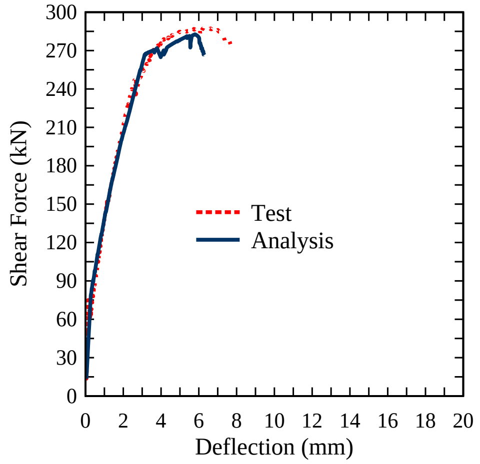
The experimental shear force-deflection relationship of each of the four SC beams s illustrated by the dashed curve, as shown in Fig. 14. For each of Specimens SC3 and SC6, only one curve is plotted because both North and South ends of the specimen were tested simultaneously by symmetrically applied loading system. The dashed curves are compared to the solid curves, representing the analytical results. It can be seen from the figure that good agreement is obtained for the initial stiffness, the peak strength, the ductilityand the descending branch.As mentioned before, all the tested SC beams have bond-slip failure mode due to the insufficiency of bond stress between concrete and steel plates. It is observed from the analyses that all descending parts of the analytical shear force-displacement curves wereobtained when the stress-strain behavior of the bottom truss element reaches the descending region in the stress-strain curve of the proposed material model; therefore, the finite element model is able to capturethe failure modes of the test specimens.



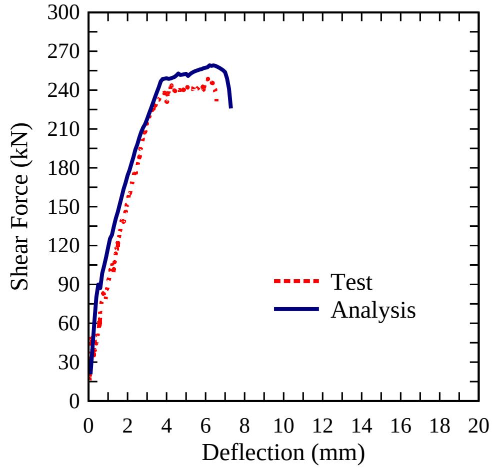


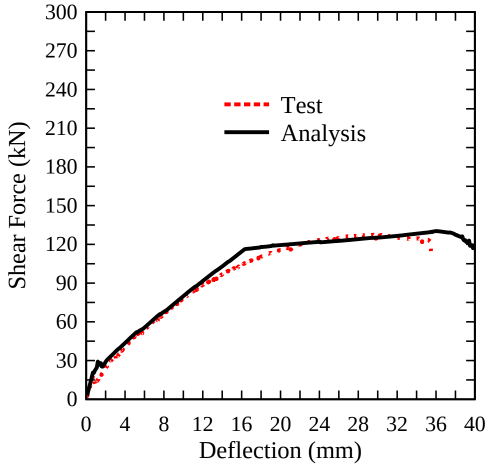
SC3 SC4 North





SC4 South SC5 South





SC5North SC6

Fig. 14Simulated and experimental shear force-deflection curves of each specimen

Table 2 provides the comparison of the analytical and experimental results regarding the shear strength of the SC beams tested in this work. In general, all the predicted and experimental values match quite well.

The mean of the test-to-analysis shear strength ratio is 1.01with a coefficient of variation (COV) of 0.06, which is well within the acceptable limit in structural engineering.

Table 2 Experimental Verification

Specimen	$V_{max,\ test}$ (kN)	$V_{max,\ analysis}$ (kN)	$\frac{V_{max,\ test}}{V_{max,\ analysis}}$
SC3	155.4	138.2	1.12
SC4 North	190.0	199.9	0.95
SC4 South	235.7	229.9	1.03
SC5 South	248.8	259.1	0.96
SC5 North	288.0	282.7	1.02
SC6	127.6	130.3	0.98
		AVG	1.01
		COV	0.06

VII. Conclusions

In the paper a new analytical model was developed to predict the structural behavior of SC beams subjected to shear.In this study, the investigated SC beams showed complex structural behavior, which was a combination of shear behavior of concrete web with cross ties and flexural bond-slip behavior of steel plates. The CSMM model, which had been developed for simulation of shear behavior for RC structure was utilized to capture the shear behavior of concrete web with cross ties. Additionally, a new constitutive model was proposed to account for the bond-slip behavior of steel plates. The proposed model was successfully implemented into a finite element analysis program SCS based on the framework of OpenSees. The developed program was capable of accurately predicting the shear force-displacement curves of all four tested SC beams. The finite element simulation developed in this paper provides researchers and engineers with a powerful tool to perform analysis and design SC structures.

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