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Composite and Modular Structures, Part 2

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Kadir Sener is a graduate research assistant in the School of Civil Engineering at Purdue University, working towards his PhD. He earned his BSCE degree from Istanbul Technical University, Istanbul, Turkey in 2007. His research interests include the behavior of steel plate reinforced concrete modular walls subjected to mechanical and thermal loads.

OUT-OF-PLANE SHEAR BEHAVIOR OF SC COMPOSITE STRUCTURES

Kadir C. Sener, Amit H. Varma
Purdue Univ., West Lafayette, IN, USA
Sanjeev R. Malushte
Bechtel Power Corp.
Keith Coogler
Westinghouse Electric Corp.

Research Background

- Out-of-plane shear strength of SC walls for nuclear power plant application have been investigated by researchers in Japan, Korea and US.
- SC beams were tested with parameters being;
  - Usage of combination of shear studs, tie bars and plate stiffener members (ribs)
  - Loading and support configuration
  - Shear span to depth ratio (a/d)
  - Steel plate and tie bar reinforcement ratios (ρ_s)
  - Full scale vs. scaled specimen

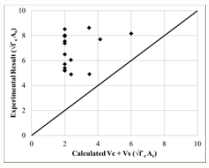
Research Background

- Japanese Test Program - Takeuchi, Masayuki et al., (1999)

- 16 SC beams were tested having only shear studs and tie bars and both.
  - Specimens with shear span-to-depth ratio less than 1.5 except three specimens having 2.6
  - Plate reinforcement ratios ranging from 1.33-4%
  - Section depths vary from 9 - 27 in. Thus the specimens are 1:6 to 1:2 scale with reference to current SC walls
  - The average stud spacing-to-plate thickness (s/t_p) ratio for specimens was 28

Research Background

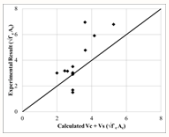
- Japanese Test Program - Takeuchi, Masayuki et al., (1999)



- The shear span ratios for tested specimens were small resulting in significant arching effects and large shear strength values
- As the shear-span ratios increased, comparable strength values with ACI equations were obtained

Research Background

- ❖ Korean Test Program - Hong, Lee et al., (2009)
  13 SC beams were tested having shear studs and tie bars and ribs.



- o Comparable shear strength values to ACI equations for most beams. However for some specimens the a/d ratios were on the lower side so they did not capture the lower bound strength
- o In the large a/d ratio beams the flexural capacity was achieved before shear capacity

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Approach and Objectives

- o Investigate the lower bound shear strength of SC beams with or without shear reinforcement
- o Applicability of current RC design code (ACI 349, JEAG 4618) equations to steel-plate composite (SC) construction are investigated

$$V_n = V_c + V_s$$
$$V_c = 2\sqrt{f'_c}\,A_c$$
$$V_s = A_v F_{vt}\frac{d}{s}$$

ACI 349

- o 3D solid element nonlinear finite element analysis (NIFE) using explicit time integration were performed to gain additional insight into experimental behavior.

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Purdue University Experimental Program Summary

- o Total of 8 specimens tested with three or four-point bending configuration
- o Depth to shear-span ratio ranged from 2.5 to 5.5 in order to investigate the lower bound shear strength
- o Two sets of specimens to clearly understand major contributors to the out-of-plane shear strength
  - without shear reinforcement (5 specimens)
  - with shear reinforcement (3 specimens)
- o Other parameters for the specimens are steel plate thickness, shear stud spacing and specimen size.

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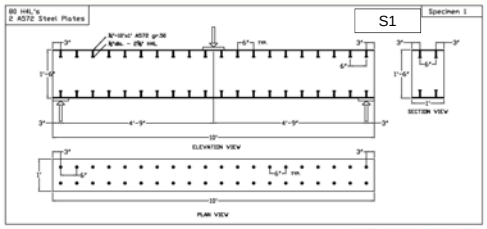
Experimental Program Details

- o 5 specimens without shear reinforcement
  - 4 specimens (half scale) tested in three-point bending (S1~S4)
  - 1 specimen (large scale) under four-point bending (S5)
  - All specimens with ¾ in. self-consolidating concrete



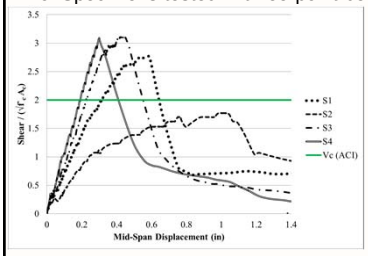
Experimental Results

- o 5 specimens without shear reinforcement

Specimen	L, (in)	b_w (in)	t_p (in)	d_v (in)	a_v/d	s/t_s	ρ_v (%)	f'_c (ksi)	f_{y_plate} (ksi)	Loading Configuration	$\frac{V_{test}}{(b_v d\sqrt{f'_c})}$	$\frac{V_{test}}{V_c}$ (ACI)
S1	120	12	0.25	17½	3.20	24	2.78	6.1	65	3-point	2.77	1.38
S2	120	12	0.25	17½	3.25	36	2.78	6.1	65	3-point	1.77	0.88
S3	120	12	0.375	17¼	3.20	16	4.17	6.1	65	3-point	3.09	1.55
S4	96	12	0.25	17½	2.50	24	2.78	6.1	65	3-point	3.11	1.56
S5	396	34¼	0. 5	35	3.50	20	2.78	6.2	71	4-point	1.90	0.95

Experimental Results

- o Specimens tested in three-point bending (S1~S4)



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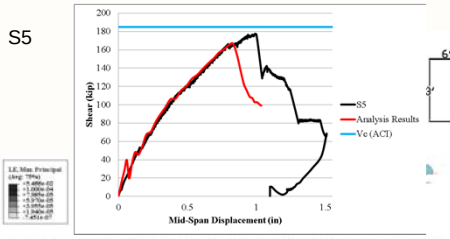
Non Linear Finite Element (NIFE) Analysis Approach

- The explicit dynamic analysis method was used for all the analyses due to advanced capability in handling nonlinear problems including significant contact
- The built in concrete material models in ABAQUS that are available for explicit dynamic analysis were used to account for cracking and multi-axial constitutive behavior
- Ductile damage is defined in tie bars and shear studs (embedded in concrete) to capture the rupturing of steel portions when ultimate strain is reached

Experimental and 3D NIFE Analysis Results

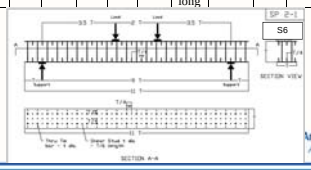
- S5



Experimental Results

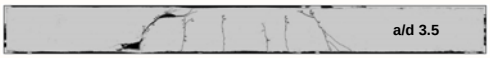
- 3 specimens with shear reinforcement

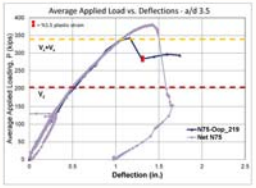
Specimen	L, (T)	b_w, (T)	t_p, (t)	d, (T)	a_v/d	S_{stud}, (T)	S_{tie_bar}, (T)	*Shear stud type*	*Tie Bar type*	ρ, (%)	f'_c (ksi)	f_{y_plate} (ksi)	f_{y_stud} (ksi)	$f_{y\_tie\_bar}$ (ksi)
S6	11	1	1	1	3.5	¼	½	t dia – T/6 long	t dia	2.17	7	58	61.5	83.5
S7	7	1	1	1	2.5	¼	½	t dia – T/6 long	t dia	2.17	7.6	62	61.5	83.5
S8	13.3	1	1	1	5.5	¼	½	t dia – T/6 long	t dia	2.17	7.5	56	61.5	83.5

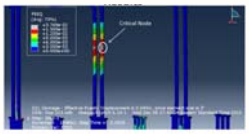


Experimental and 3D NIFE Analysis Results

- S6 with shear reinforcement



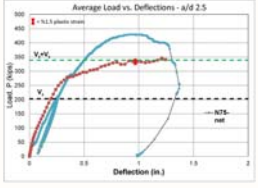




Tie bar failure

Experimental and 3D NIFE Analysis Results

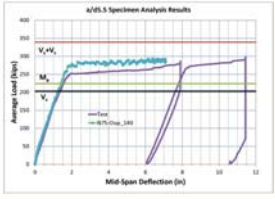
- S7 with shear reinforcement

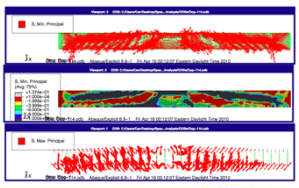


Rupture in tie bars

Experimental and 3D NIFE Analysis Results

- S8 with shear reinforcement





Conclusions and Recommendations

- ACI code equations for reinforced concrete beams may be used for evaluating the out-of-plane shear strength of SC structures as a lower bound
- The behavior is predicted reasonably using nonlinear inelastic finite element analysis in the most part of the response
- Size effect in out-of-plane shear strength is observed for specimens that did not have shear reinforcement

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Conclusions and Recommendations02

- In order to determine the lower bound shear strength for SC beams, it is recommended that the out-of-plane shear tests be conducted for shear span ratios (a/d) in the range of 3.0-3.5

- Additional research is needed to further evaluate and confirm the findings for a wide range of parameters, and including cyclic loading effects, concurrent axial tension effects and accidental thermal

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