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EXPERIMENTAL INVESTIGATION OF SLIDING ON COMPACT SLIDING SPECIMENS UNDER CYCLIC LOADS

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ABSTACT

This experimental investigation addresses the sliding behaviour found to occur in reinforced concrete shear walls under earthquake loads. This investigation compromises a series of 13 compact specimens. The tests were conducted in a biaxial test setup. The test sequences were designed to mimic the load and displacement history of a portion of the squat wall under horizontal cyclic loading. The specimens were pre-cracked up to a defined crack width. Next, diagonal compression was applied. Through the variation of the reinforcement ratio, the initial crack width, the number of cycles and the amplitudes, the effects of aggregate interlock, dowel action and shear friction in the crack were quantified. In this paper we will present the observations and the results of the cyclic tests on the core specimen group and on the monotonically tested specimens.

INTRODUCTION

Reinforced concrete shear walls are commonly used to provide buildings with stiffness, strength and stability against horizontal earthquake loads. To design these walls, load- and deformation-based concepts can be used. Because the response spectrum method incorporates linear material properties, the capacity spectrum method and the time history method require the description of the material and geometric nonlinearities. The cyclic deformation behaviour under flexure and shear has been studied in many experiments and modeled using several approaches. The sliding mechanism and the interaction of flexure and shear with the sliding mechanism are not as well understood today (see Figure 1 on the right).

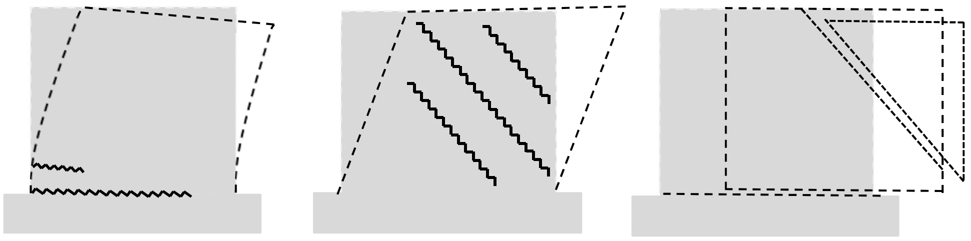

Figure 1: Deformation and resistance mechanisms of shear walls

The sliding mechanism was investigated by different researchers in the 70s and 80s [Walraven and Reinhardt (1981), Mattock (1976), Nissen (1987), Jimenez Perez and White (1978) and Laible *et*

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al. (1977)]. Jimenez Perez and White (1978) and Laible *et al.* (1977) conducted cyclic sliding tests. Although a wide range of parameters was examined, two parameters, essential for the seismic design of reinforced concrete walls, have not been sufficiently investigated in the tests mentioned above. They are:

- *Initial crack width*: depending on the applied reinforcement ratio, reinforcement quality and the concrete strength, large crack widths, as wide as 1 to 3 mm, have to be considered.
- *Post peak behavior*: most of the tests to date were aborted shortly after the maximum shear resistance was attained. Thus, the load displacement relationship, the degradation of resistance and the ability to dissipate energy were only partially investigated.

EXPERIMENTAL INVESTIGATION

Sliding in shear walls occurs along a horizontal flexural crack at the base of the wall or at the joint between a structural wall and the basement ceiling [Schuler and Trost (2014)]. The resistance to sliding is a result of dowel action and aggregate interlock along the open portion of the crack and the interaction of compression, shear, dowel action, aggregate interlock, and friction along the closed portion of the crack. The objective of the experimental investigation is to examine the behavior in the cracked compressed zone of a shear wall flexural crack under applied cyclic lateral load. A compact reinforced concrete specimen and the biaxial test setup designed to achieve this goal are described in the next section.

Compact sliding specimens:

The compact sliding specimen is a reinforced concrete block with the dimensions l/h/t=420/420/120 mm (see Figure 2). The specimens were cast in the horizontal position in two phases to make a cold joint in the middle of the specimen. This cold joint simulates the horizontal flexural crack at the base of a shear wall. The form was separated into two parts using a formwork board. The inside of the board was coated with retarder (Rugasol®-1S Paste). The separating board was removed 48 hours later, and the cold joint was cleaned with a pressure washer. This procedure ensured a rough and robust surface at the cold joint. The second section of the specimens was cast seven days later (see Figure 3). The age of the concrete in the specimens was at least 28 days at the day of the test. The concrete compression strength was evaluated for each casting phase. The average compression cube strength of all specimens is 30.3 N/mm². The maximum aggregate size used to make the concrete for the specimens was 16 mm.

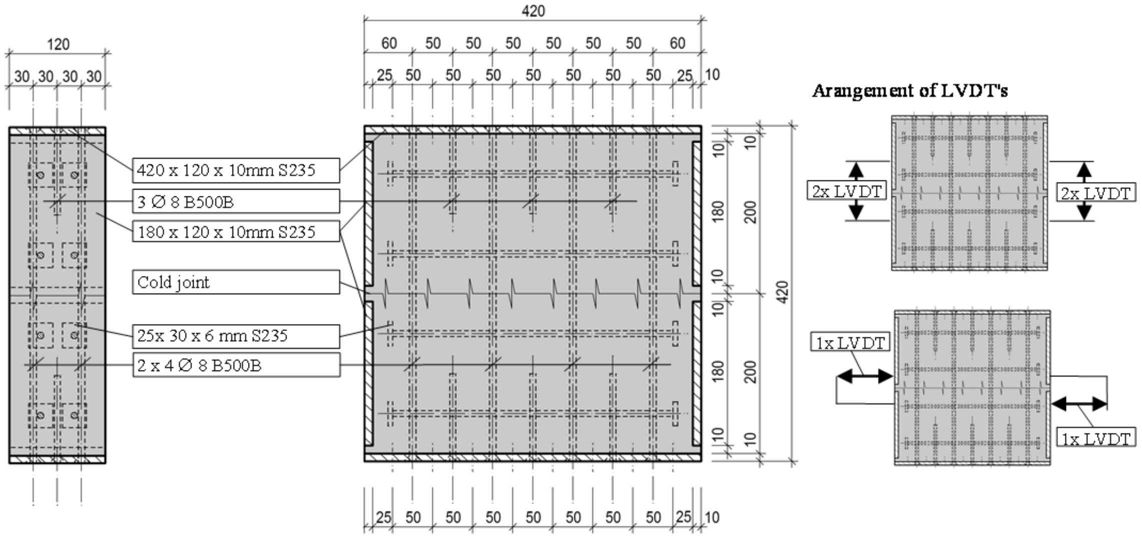


Figure 2: Compact sliding specimen

The vertical (y-direction) reinforcement is welded to the upper and the lower steel plates (l/h/t=420/120/10 mm), as shown in Figure 2. The horizontal (x-direction) reinforcement is anchored using small steel head plates l/h/t=25/30/6 mm. Additionally, 110 mm long reinforcement bars that do not reach the cold joint are welded on the upper and lower steel plate to strengthen the connection between the concrete and the steel plates to prevent the occurrence of large cracks between the steel plates and the concrete. Horizontal load transfer steel plates (l/h/t=180/120/10 mm) are connected to the concrete of the specimen using small screws (2 x M6). The average tensile strength of the reinforcement is 615 N/mm².

Figure 3: Compact specimen construction

Test setup:

The test load and displacement sequence was designed to simulate the force and displacement state of the compressed portion of the horizontal flexural crack at the base of a shear wall. First, the specimens were pre-cracked up to a defined crack width using a vertically positioned actuator (see Figure 4, left). This actuator was positioned above the specimens to produce centric tension. The crack widths were measured using 4 LVDT (**l**inear **v**ariable **d**ifferential **t**ransformer), one on each edge of the specimen. The actuator was controlled by displacement control and moved with a velocity of 0.02 mm/s. The actuator load was removed when the average crack width reached the target value.

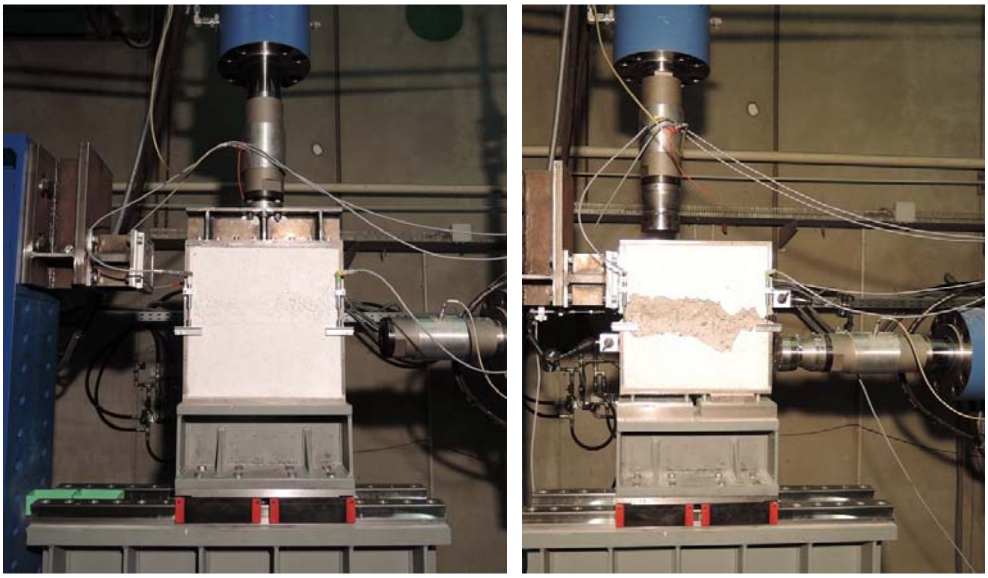


Figure 4: Test setup

Next, the vertical cylinder was moved to the side in order to apply compression at an angle of 45° to the cold joint (see Figure 4, right). The specimens were supported by a PTFE (polytetrafluoroethylene) bearing in the horizontal direction and by a sliding bearing in the vertical direction. The horizontal cylinder was displacement-controlled and moved with a velocity of 0.05 mm/s following a prescribed cyclic displacement sequence. The resistance of the specimen produces the measured horizontal reaction force. The vertical hydraulic cylinder was synchronized to the force of the horizontal cylinder. Two LVDTs, one on the left and the other on the right side of the specimen, measured the horizontal displacement between the upper part and the lower part of the specimens. The attachments were positioned close to the crack to reduce the influence of possible rotations.

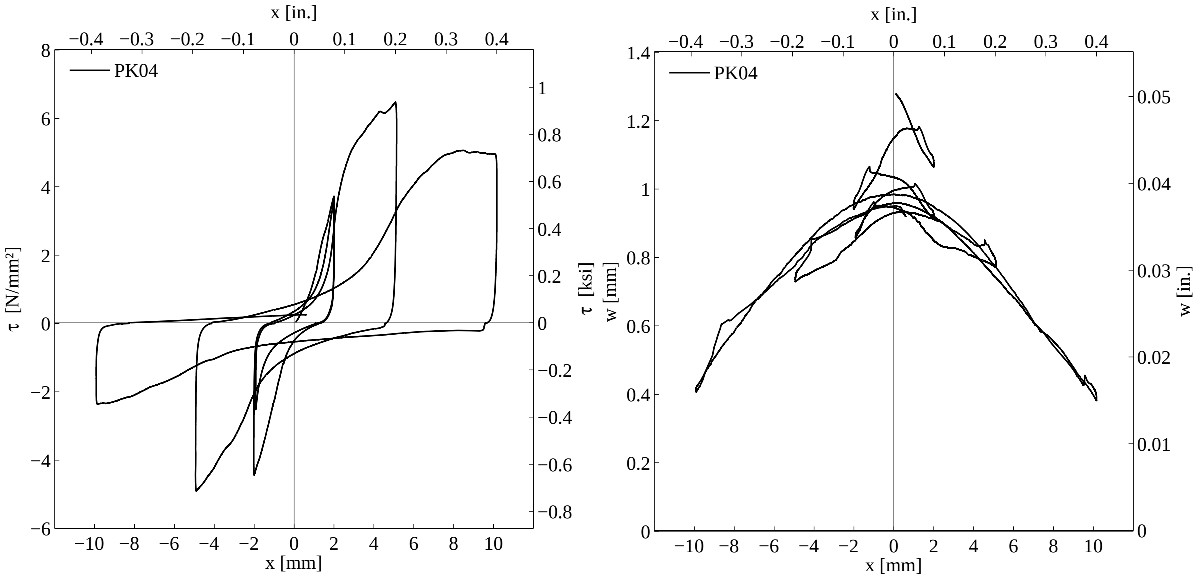
Under load, the two halves of the specimens shifted against each other, moving both in the horizontal and the vertical direction. The actuator loads were removed when the average displacement of the two LVDTs reached the target amplitude. The specimen was turned in the opposite direction and loaded again until the same absolute displacement amplitude was reached in the other direction. Next, the specimen was turned again and loaded to the next target amplitude. This procedure was repeated several times, for the purpose of cyclic loading, except in the case of monotonic loading.

EXPERIMENT OUTCOMES AND DATA

The tests on the core specimen group of five identical specimens with the reinforcement ratio of 0.83% are described here. Each specimen was pre-cracked to make a 2-mm crack at the cold joint. Specimens PK02, PK03 and PK04 were cycled through four full cycles (2 mm twice, 5 mm and 10 mm) under diagonal compression, while specimens PK05 and PK11 were loaded monotonically to failure.

Specimens PK02, PK03 and PK04: Cyclic loading

The response of Specimen PK4 is shown in Figure 5 (a), where the abscissa shows the relative horizontal displacement between the upper part and the lower part of the specimen, and the ordinate shows the horizontal shear stress; and in Figure 5 (b), where the relative horizontal displacement vs. the change of the average specimen crack width w_{crack} is plotted.



a) Shear stress versus displacement **b) Crack width versus displacement**

Figure 5: Test results for Specimen PK04

Specimen PK04 was pre-cracked under centric tension load to a crack width of 2 mm. An average crack width (vertical distance between the two parts of the specimen) of 1.31 mm remained after the tension load was removed. In the next phase, diagonal compression was applied. One half cycle describes the relative horizontal displacement between the upper part and the lower part of the specimen from 0 mm to the cycle amplitude in one direction and back to 0 mm. During the 1st 2-mm displacement half cycle, the response was almost completely linear: the specimen stiffened slightly. The maximum shear stress of 3.72 N/mm² was reached at the displacement amplitude of 2 mm (see Table 1). After the load was removed, the permanent relative vertical displacement between the upper part and the lower part was 1.26 mm. Subsequently, the specimen was loaded in the opposite direction under diagonal compression. Under load, the crack closed by 0.24 mm. When the load was removed, the crack opened 0.11 mm and a permanent crack width of 1.18 mm remained (see Table 2). The crack continued closing when the force was applied in the opposite direction, with a permanent crack width of 1.15 mm at the end of the next half cycle. During the 1st and the 2nd half cycle, the crack closed approximately twice as much as it opened, while in 3rd and 4th half cycle, the crack opening and closing was about the same. Virtually no strength degradation occurred during the 1st, 2nd and 3rd half cycles to 2 mm, with the average maximum shear stress of 3.9 N/mm². Significant degradation occurred in the 4th half cycle with the maximum shear stress of 2.5 N/mm². The opening and closing of the crack behaved differently.

The peak shear resistance in the first 5-mm half cycle was 6.5 N/mm². The start of this half cycle was similar to the 2-mm cycles. After approximately 2.5 mm displacement, the response entered a softening range. The crack width behavior of this half cycle also changed. The crack closed under load, to a crack width of 0.77 mm at the displacement amplitude of 5 mm, and opened under load removal, but it continued to open even when diagonal compression was applied in the opposite direction, making the plot in Figure 5 (b) somewhat asymmetric. The crack width at 0 mm differential displacement didn't change significantly. In the 2nd 5-mm half cycle, the shear resistance dropped to 4.9 N/mm².

Although the shear resistance attained in the 1st 10-mm half cycle was 5.1 N/mm², the stiffness degradation was obvious. The process continued in the 2nd 10-mm half cycle when the maximum shear stress was only 2.36 N/mm². The change of the crack width was steady: the crack was closed in proportion to the relative displacements and opened to its maximum when the relative displacement was 0 mm.

Table 1. Maximum shear stress recorded during tests with Specimens PK2, PK3 and PK4

		τ_{max}			
		ρ=0.83			
x_{max}		**PK2**	**PK3**	**PK4**	**avg.**
mm	**half cycle**	N/mm²	N/mm²	N/mm²	N/mm²
2.0	**1st**	5.1	5.1	3.7	4.6
	2nd	5.3	4.5	4.4	4.7
	3rd	5.3	4.8	3.6	4.6
	4th	1.5	3.6	2.5	2.5
5.0	**1st**	6.8	6.7	6.5	6.7
	2nd	4.5	4.3	4.9	4.6
10.0	**1st**	4.7	4.3	5.1	4.7
	2nd	2.6	2.5	2.4	2.5

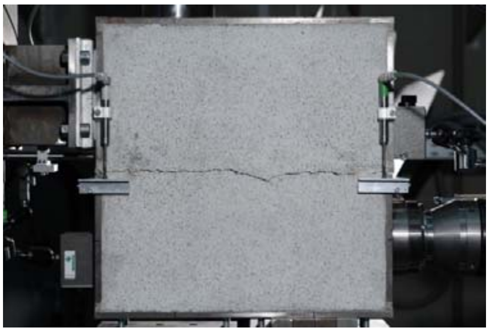
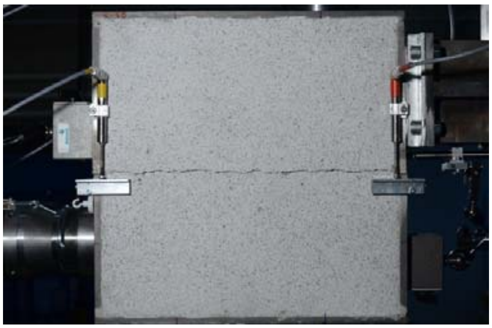
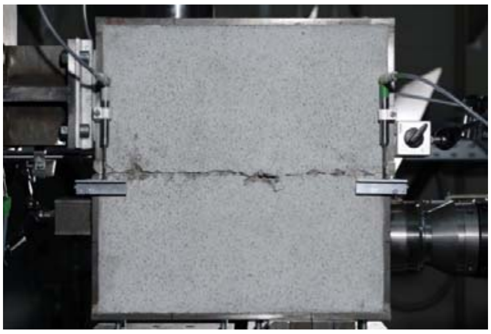
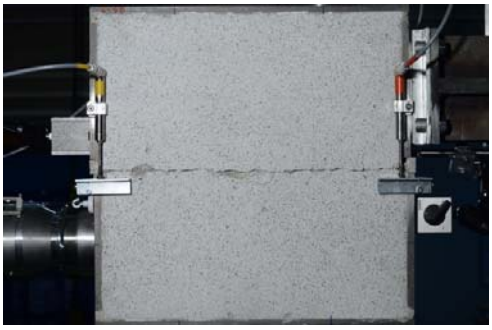
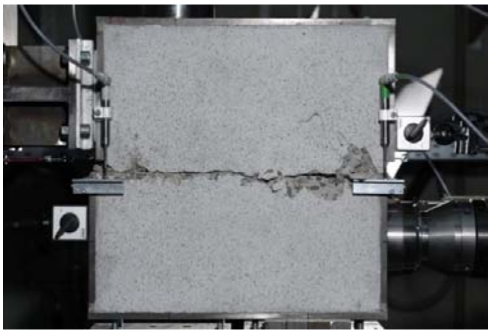
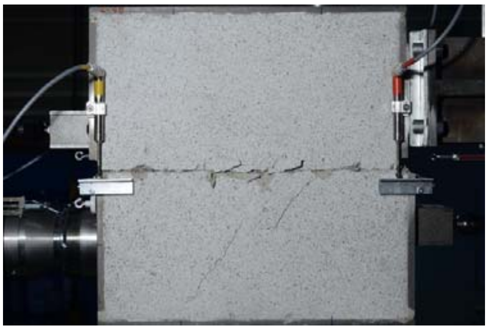
Pictures of Specimen PK4 are shown in Table 3. Surface A and Surface B are describing the front and the back side of the specimen. The pictures were taken at the maximum horizontal displacement of the 1st 2 mm, 5 mm and 10 mm half cycles. Almost no damage was visible after the first 2 mm half cycles. Small cracks and local spalling of the concrete cover were observable at the maximum amplitude of the 1st 5 mm half cycle. Major diagonal cracking and damage occurred during the 10 mm half cycle. Damage to the horizontal crack surface started to develop after the peak shear was reached.

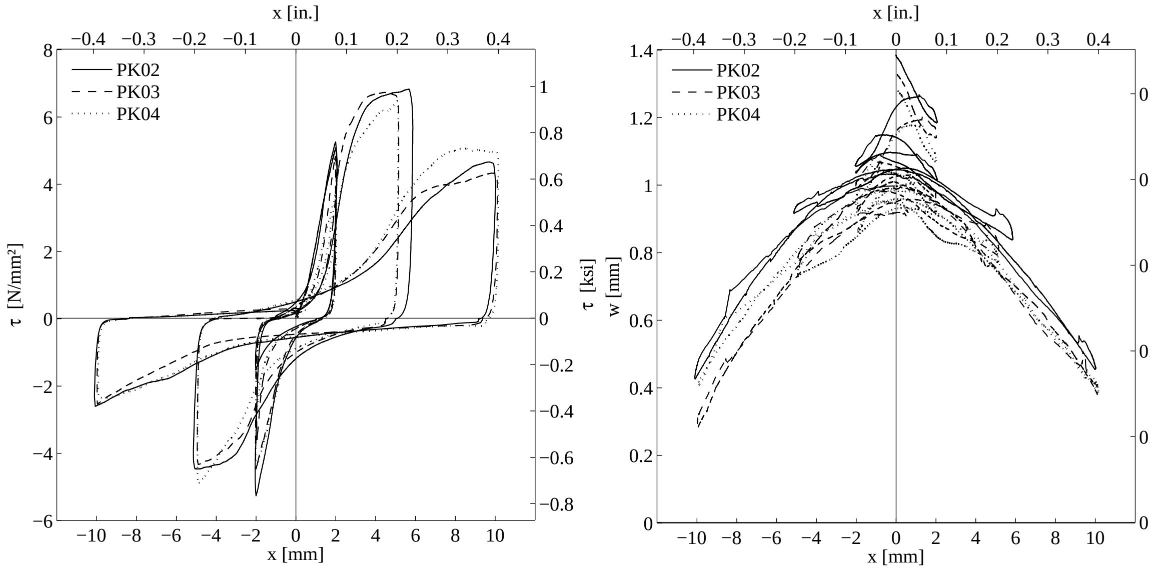
The responses of the core group Specimens PK02, PK03 and PK04 are compared in Table 2 and Figure 6. The average crack width remaining after tension load removal was 1.34 mm. The load-displacement responses of these three specimens are very similar. All specimens reached the maximum shear resistance during the 1st 5-mm half cycle. The crack width behavior recorded during the tests was also similar. The average maximum shear stress was 6.7 N/mm². The cyclic sliding response of the compact sliding specimens is, therefore, repeatable.

Table 2. Change in crack width in Specimens PK2, PK3 and PK4

		w_{crack}											
		lateral def.: x = 0 mm				**lateral def.: x = min / max**				**τ = 0**			
x_{max} mm	**half** **cycle**	**PK2** mm	**PK3** mm	**PK4** mm	**avg.** mm	**PK2** mm	**PK3** mm	**PK4** mm	**avg.** Mm	**PK2** mm	**PK3** mm	**PK4** mm	**avg.** mm
	0	1.39	1.33	1.31	1.34								
2.0	**1st**	1.23	1.16	1.15	1.18	1.18	1.14	1.07	1.13	1.27	1.20	1.18	1.22
	2nd	1.14	1.06	1.03	1.08	1.06	0.99	0.94	0.99	1.15	1.08	1.06	1.10
	3rd	1.10	1.03	1.00	1.04	1.01	0.96	0.92	0.96	1.09	1.03	1.02	1.05
	4th	1.07	0.97	0.95	1.00	1.04	0.92	0.86	0.94	1.09	0.99	0.96	1.01
5.0	**1st**	1.05	0.95	0.93	0.98	0.84	0.79	0.77	0.80	0.93	0.89	0.85	0.89
	2nd	1.05	1.01	0.96	1.00	0.91	0.77	0.73	0.80	0.98	0.88	0.82	0.89
10.0	**1st**	1.03	0.99	0.98	1.00	0.45	0.38	0.38	0.41	0.55	0.50	0.45	0.50
	2nd	1.00	0.92	0.98	0.97	0.43	0.28	0.41	0.37	0.61	0.48	0.60	0.57

Table 3. Pictures of Specimen PK4

		PK4	
		lateral def.: x = min / max	
x_{max} mm	**half cycle**	**Surface A**	**Surface B**
2.0	**1st**		
5.0	**1st**		
10.0	**1st**		



a) Shear stress versus displacement

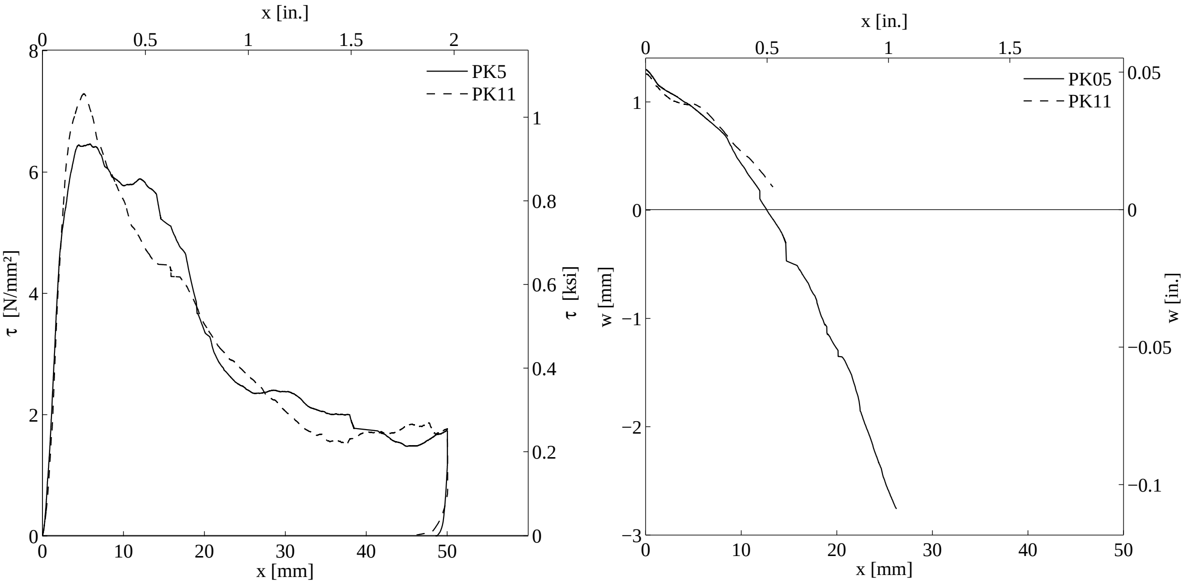
b) Crack width versus displacement

Figure 6: Comparison of the responses of Specimens PK02, PK03 and PK04

Specimens PK05 and PK11: Monotonic loading

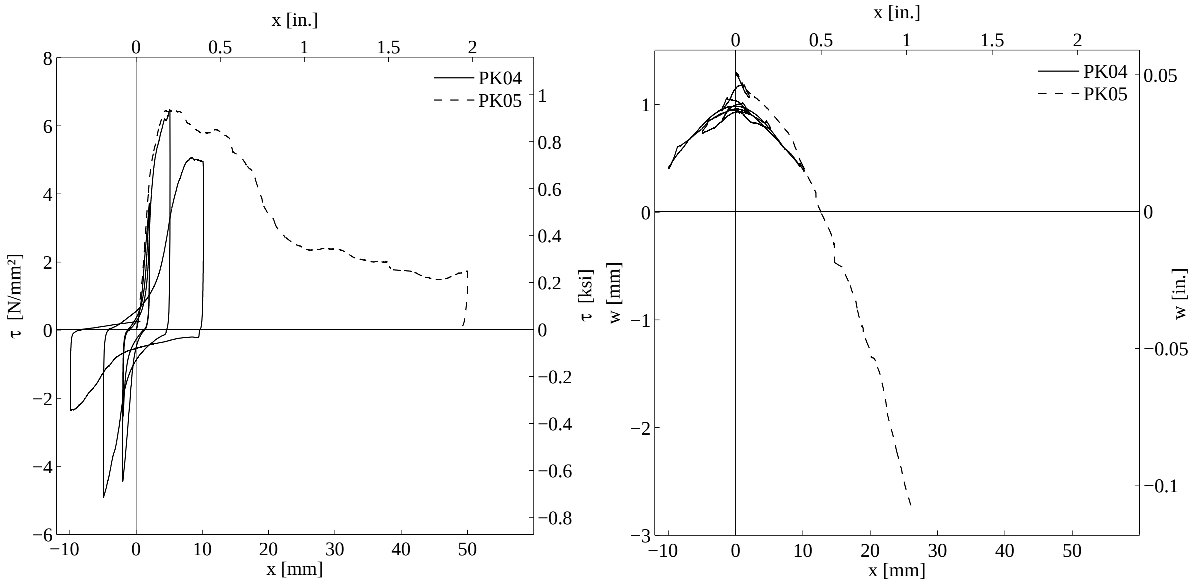
Specimens PK05 and PK11 are the same as Specimens PK02, PK03 and PK04, the only difference being that after being pre-cracked to 2 mm, they were monotonically loaded to failure due to diagonal compression. The response plots are shown in Figure 7. The average peak shear stress of 6.9 N/mm² was reached at an average horizontal displacement of 5.5 mm. The tests were stopped at a displacement of 50 mm. The measurement of the crack width stopped earlier because the anchorage of the LVDT's was destroyed by the spalling concrete cover. The LVDT measurements of crack width were discontinued at 26 mm of displacement because the instrument anchor points were damaged and became loose.

The obtained monotonic shear stress horizontal deformation response plots envelope the cyclic response plot, as shown in Figure 8 which compares the responses of Specimens PK04 and PK05. The cyclically loaded specimens attain the same strength as the monotonically loaded ones in the first half cycle to a new displacement magnitude. This applies in the post-peak response range, where the specimens soften, if the new displacement amplitude is substantially larger than the amplitude of the previous displacement cycle. When the cyclic specimens reach the monotonic response envelope, their response follows that of the monotonically tested specimens.



a) Shear stress versus displacement **b) Crack width versus displacement**

Figure 7: Response of Specimens PK05 and PK11

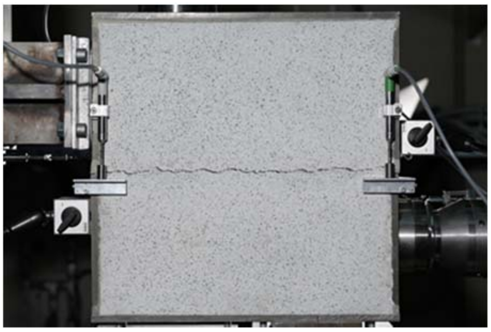
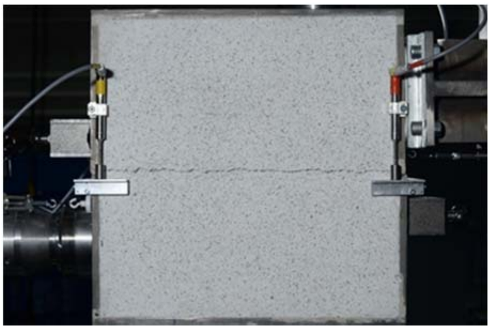
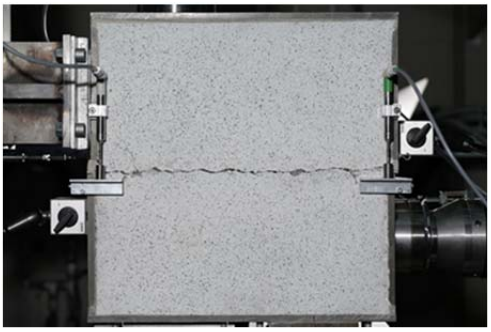
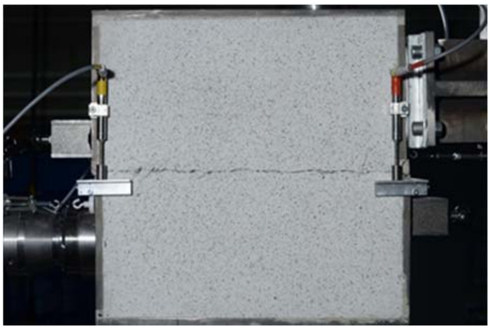
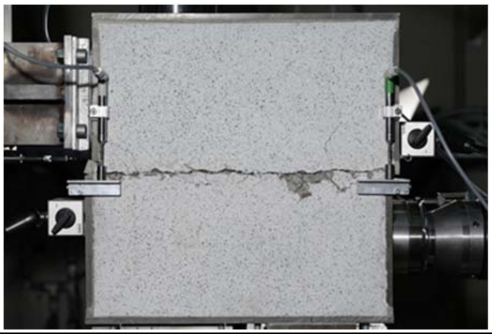
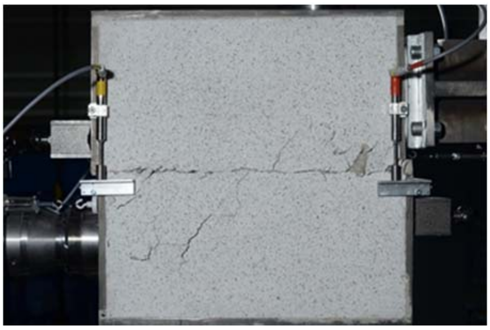
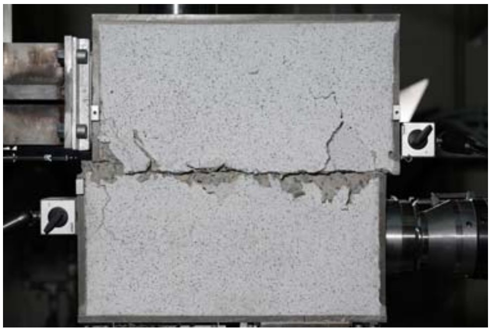
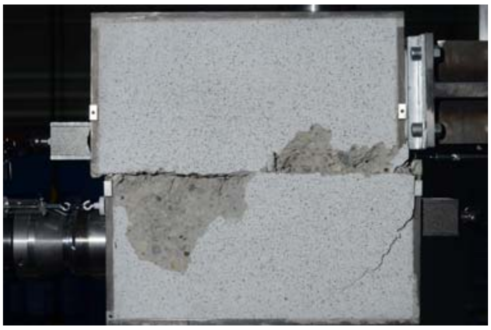
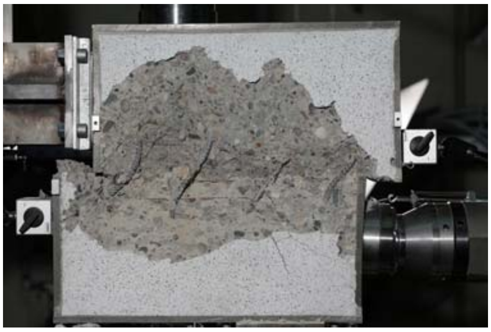


a) Shear stress versus displacement **b) Crack width versus displacement**

Figure 8: Response of Specimens PK04 and PK05

Table 4 shows the photos taken at different displacement stages during the test with Specimen PK11. The visible damage on the surface is similar to that observed during the cyclic Specimen PK04 test. Almost no damage is visible at the horizontal displacement of 2 mm. At 5mm, small cracks are visible. At 10 mm, major diagonal cracks are developing and the concrete cover close to the cold joint starts to spall. At 20 mm, the concrete cover has spalled in the direct surrounding area, although large cracks developing in a wide area of the specimen and large parts of the concrete cover are starting to spall. At 50 mm, major parts of the concrete cover have spalled and the vertically bent reinforcement bars are visible.

Table 4. Pictures of Specimen PK11

x mm	**PK11**	
	lateral def.: x	
	Surface A	**Surface B**
2.0		
5.0		
10.0		
20.0		
50.0		

CONCLUSIONS

Sliding is one of the three possible deformation response modes of reinforced concrete shear walls under horizontal loads. The flexure and shear response modes are well understood. The tests presented herein are a part of a comprehensive project aimed at understanding and modeling the sliding deformation mode and the interaction between sliding, flexure and shear in reinforced concrete shear walls. The compact sliding specimens represent the compressed portion of the horizontal flexural crack at the base of the shear wall. The specimens were manufactured with a horizontal cold joint. They were pre-cracked using a centric tension load to generate an open horizontal crack. Then, the specimens were tested under diagonal compression by applying coordinated horizontal displacement and vertical compression using monotonic or cyclic displacement histories.

The behavior and test results obtained from tests of five identical specimens (reinforcement ratio of 0.83% and pre-crack width of 2 mm) were presented in this paper. Three specimens were tested under cyclic horizontal loading and two were monotonically pushed to failure. The following conclusions can be drawn:

1. The load-deformation response plots obtained from the monotonic tests envelope the load-deformation responses of the cyclically tested specimens, both before the peak strength is attained (in the stiffening response range) and in the post-peak (softening) response range.
2. The peak shear stress attained by the specimens was between 6.7 and 6.9 N/mm² and occurred at horizontal displacements of between 5 and 6 mm.
3. The attainment of peak resistance coincides with visible cracking in the region near the horizontal crack, followed by spalling of the concrete cover and damage to the horizontal crack surface.
4. The softening observed during the compact specimens tests was significant, with the shear resistance dropping to approximately 1/3rd of the peak value at the horizontal displacement of 30 mm and then remaining constant.
5. The sliding stiffness of the cyclically loaded specimens degrades. The degradation rate depends on the number of cycles and the displacement magnitude. The rate is small before the peak resistance is attained, but accelerates significantly in the post-peak range.
6. The horizontal crack pre-cracked to a 2-mm initial opening remains open under diagonal compression for horizontal displacements of up to 10 mm.

Testing of compact sliding specimens with different reinforcement ratios and initial crack opening magnitudes is ongoing. The results of the entire test series is expected to provide insight into the interaction of the reinforcement dowel action, aggregate interlock and shear friction resistance mechanisms along the horizontal crack surface.

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