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PREVENTING PUNCHING SHEAR FAILURES OF REINFORCED CONCRETE SLABS; RESULTS OF STATIC AND PSEUDO-SEISMIC TESTS ON SHEAR BOLT RETROFITTED SLABS

ZAPOBIEGANIE PRZEBICIU PŁYT ŻELBETOWYCH ZA POMOCĄ SKRĘCANIA ŚRUBAMI

Abstract The paper presents research program on retrofitting reinforced concrete slab-column connections to increase their punching shear strength and ductility. The proposed technique using shear bolt reinforcement allows increasing strength, ductility and rotational capacity of reinforced concrete slab-column connections which are essential for ensuring structural integrity and preventing progressive collapse of such systems. The method allows repair and strengthening of existing, previously built, flat reinforced concrete slabs supported on columns, which do not have adequate punching shear strength at the column area. Steel shear bolts, which were developed at the University of Waterloo, are new type of reinforcement for retrofitting of existing, previously built, flat slabs. The shear bolt consists of a headed steel rod threaded at the other end for anchoring using a washer and nut system. The bolts are installed in holes drilled in a slab in concentric perimeters around the column. The results of the experimental work include twenty three large-scale reinforced concrete slab-column connections tested under static and reversed cycling horizontal loads. The performance of strengthened slabs is shown in a form of load-displacement curves and hysteretic response, which demonstrate how transverse reinforcements increase punching shear capacity, ductility and energy dissipation capability of slab-column connections.

Streszczenie W pracy przedstawiono program badawczy dotyczący modernizacji połączeń płyt żelbetowych wspartych na słupach, tak by nastąpiła poprawa ich ciągliwości oraz wytrzymałości na przebicie. Zaproponowana technika – stosująca zbrojenie za pomocą śrub – pozwala na wzrost wytrzymałości, ciągliwości i zdolności do obrotu wzmocnionych połączeń płyt żelbetowych ze słupami, co jest istotne dla zapewnienia integralności konstrukcji i zapobiegnięcia katastrofie postępującej takich układów. Metoda pozwala na reperacje i wzmocnienia istniejących, dawniej zbudowanych zbrojonych płyt betonowych wspartych na słupach, które nie mają odpowiedniej wytrzymałości na ścinanie w pobliżu słupów. Stalowe śruby, opracowane na Uniwersytecie Waterloo, stanowią nowy rodzaj zbrojenia dla modernizacji istniejących płaskich płyt. Śruba składa się ze stalowego pręta zakończonego łbem, gwintowanego z drugiego końca tak by dało się go zamocować stosując układ: podkładka + nakrętka. Śruby instaluje się w otworach wierconych w płytach, koncentrycznie wokół słupów. Testy eksperymentalne przeprowadzono na dwudziestu trzech połączeniach płyt żelbetowych ze słupami – w dużej skali – poddanych obciążeniu statycznemu i zmieniającemu się cyklicznie obciążeniu horyzontalnemu. Zachowanie się wzmocnionych płyt przedstawiono w formie krzywych obciążenie – przemieszczenie i histeretycznych odpowiedzi układu, pokazujących jak zbrojenie poprzeczne zwiększa wytrzymałość na przebicie, ciągliwość i zdolność rozpraszania energii zmodernizowanych połączeń płyta-słup.

1. Introduction

Flat reinforced concrete slab-column structural systems are easy to construct. However, some of the moist catastrophic failures occurred in such structures. The slab area around the column is subject to bending and shear actions, which cause complex three-dimensional stress and strain states and result in principal tension stresses being inclined with respect to the slab's plane. Therefore, flexural reinforcement alone cannot provide adequate ductility of these connections. Adding shear reinforcement at the column area of these slabs can substantially increase punching shear capacity and ductility, however, in many practical cases, especially in buildings designed using older codes, these shear reinforcements were not provided during construction.

Structural ductility is necessary for robustness and for avoiding progressive collapse in case of the connection's failure. Designs, according to every design code, ensure that the connection should fail in flexure before reaching its punching shear strength. This is done because flexural failures of properly designed reinforced concrete members and member connections are ductile, ensuring substantial load carrying capability and rotational capacity after yielding of the flexural reinforcement. However, flexural failures can trigger post peak punching shear failures due to extensive cracking of the concrete and corresponding reduced shear strength. Therefore, ensuring structural integrity such as to prevent progressive collapse of such structures requires that this punching failure be also ductile. This can be done if a proper shear reinforcement is placed in the slab and an adequate longitudinal integrity reinforcement is placed in the slab's compression zones.

This paper describes tests related to a retrofit method for preventing structural collapses of the reinforced concrete flat slab-column type structural systems. It concentrates on a retrofit system for existing slabs which were not reinforced for punching shear during construction. This system, shear bolts, allows strengthening slabs without extensive cost and without changing their appearance [1], [2], [3].

2. Structural collapses due to punching shear

Several cases of punching shear failures were reported in the last few decades. These occurred either during construction when shoring was removed before proper concrete strength developed, due to openings in slabs near columns, or due to construction or design errors [4].

In 1962, in New York City, a part of a roof of a car garage, collapsed suddenly [4]. The roof was supporting 1.2 m deep earth cover with vegetation on it. It was found that the slab punched through a column and there was little damage in other places of the slab. The reason was that the earth on the slab was saturated and frozen, which increased the load. It was also found that, the slab was constructed with insufficient punching shear capacity.

In 1973, the high-rise apartment building, Skyline Plaza, suffered a progressive collapse during construction. The collapse started at the 23rd floor by punching shear and progressed to the basement (Fig. 1). Fourteen workers were killed. [5].

On March 20th 1997 collapsed a part of the roof of the Pipers Row Multi-Storey Car Park that was built in 1965 [6]. The failure was due to a punching shear which developed into a progressive collapse. Pipers Row Multi-Storey Car Park was built using the Lift Slab system of construction, in which concrete floor slabs, cast at ground level, are lifted up precast columns and then supported on wedges engaging in welded angle shear collars cast into the slab. The punching shear failure occurred outside the shear head leaving the Lift Slab shear head and column connections intact. Poor concrete quality in the slabs was deemed responsible for the failure. However, this example clearly shows that column capitals cannot prevent brittleness of failure if such is to take place.

During an earthquake, the horizontal movement of the ground induces large horizontal inertia forces and lateral drifts in the buildings. The inter-story drift makes the flat slab-column connection rotate and produce moments in the connection. The moments increase punching shear stress in a concrete slab around the column area. Therefore, the flat slab structures are easy to be damaged in earthquakes. In 1985 Mexico City earthquake, 91 waffle slab structures collapsed and 44 were severely damaged [7]. This was the most vulnerable type of structure in that earthquake. Waffle-type slabs have solid slab sections at the column connections, thus they show similar behaviour to flat slab structures when punching is considered. Some of them were damaged by punching shear failure of the slabs. Others were damaged by column failures.

In the 1994 Northridge earthquake, a four-story reinforced concrete slab-column building was severely damaged. The outside perimeter consisted of ductile moment frames. Slabs (with drop panels) were post tensioned. Each of the first floor and the second floor was damaged in six slab-column connections. Also, there was cracking and spalling of concrete on the perimeter frame [8].

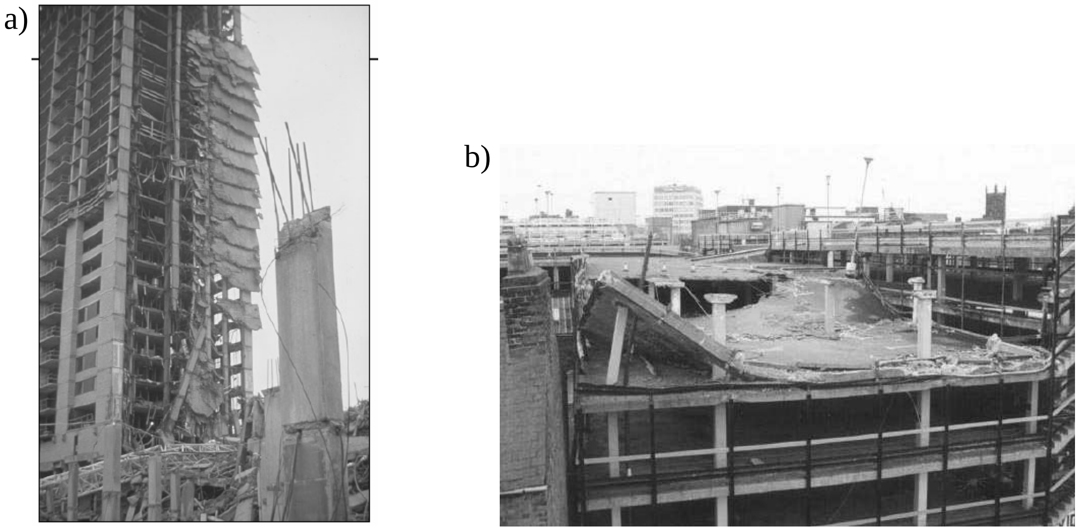


Fig. 1. Collapse of a) Skyline Plaza [11], b) Pipers Row park garage [10]

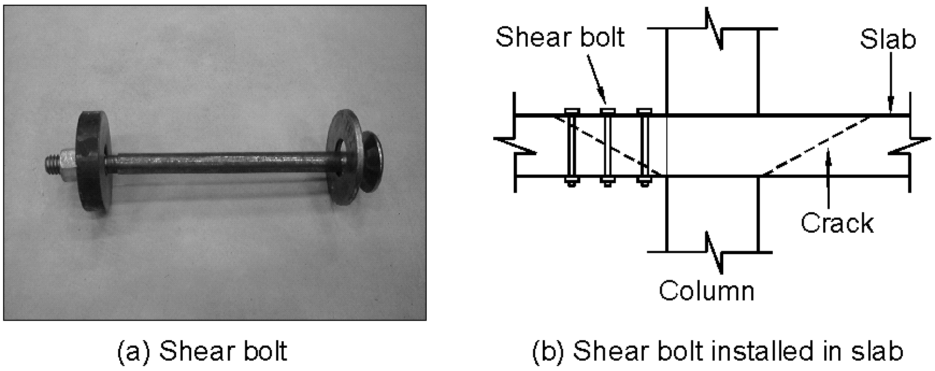
3. Shear bolts

Shear bolts, developed at the University of Waterloo, consist of a stem with a head on one end and a washer with nut at the other threaded end. The method is conceptually simple and aesthetically appealing. The retrofit involves drilling small holes in a slab, around the column area, inserting bolts into them and tightening the nut at the threaded end (Figure 2).

4. Experimental program

The presented experiments were all done at the University of Waterloo on isolated slab-column interior and edge connections under static and pseudo-dynamic loadings. The experimental program was designed to study the behaviour of slabs retrofitted with shear bolts. All specimens were full-scale and represented portions of a slab-column continuous system, bounded by the lines of contraflexure around the column. The dimensions of the specimens

(1800×1800×120 mm for interior columns with supports at 1500×1500 perimeter; and 1540×1020×120 mm for edge columns with supports at 1500×1000 perimeter) are equivalent to a portion of a typical floor system consisting of three 3.75 m bays in one direction and any number of 3.75 m bays in the other direction. Reinforcement was provided in tension (1.2% for interior, 0.75% for edge connections) and compression layers (0.55% for interior, 0.45% for edge connections) with 20 mm concrete cover to the outer bars. Some tested slabs had openings next to columns. The columns' cross sections were: 150×150 for interior static, 250×250 for edge static, and 200×200 for interior pseudo-seismic tests. Two edge slabs were strengthened with FRP laminates and shear bolts. The specimens were simply supported along the edges with corners restrained from lifting (static loading), or with the edge normal to horizontal load restrained from lifting (pseudo-dynamic tests). To allow for some rotation at the supports, the slabs were placed on neoprene pads attached to W-shape steel beams. The pseudo-dynamic test specimens were subjected to a vertical constant load (Table 1), simulating gravity loads and cyclic reversed lateral displacements simulating seismic event. The top and bottom column stubs extending 700mm from the center of the slab were used for application of the horizontal displacements. The static tests, edge and interior connections, include 14 specimens (including control specimens), while pseudo-dynamic tests were done on 9 specimens. The interior connections were strengthened with 9.5 mm diameter shear bolts placed in different number of peripheral rows around the column. The edge connections were strengthened using 12.7 mm diameter bolts. The bolts were placed either in orthogonal or radial patterns; an example is shown in Figure 3 which shows specimens with 6 peripheral rows of shear bolts. The top of the slab in the testing configuration was a compression face (under gravity loads), thus the slabs were tested in an upside down position as compared to the actual situation in buildings. The details of all presented specimens can be found in Table 1 and in [1], [2], [3].



(a) Shear bolt (b) Shear bolt installed in slab

Fig. 2. Shear bolt and its installation in concrete slab

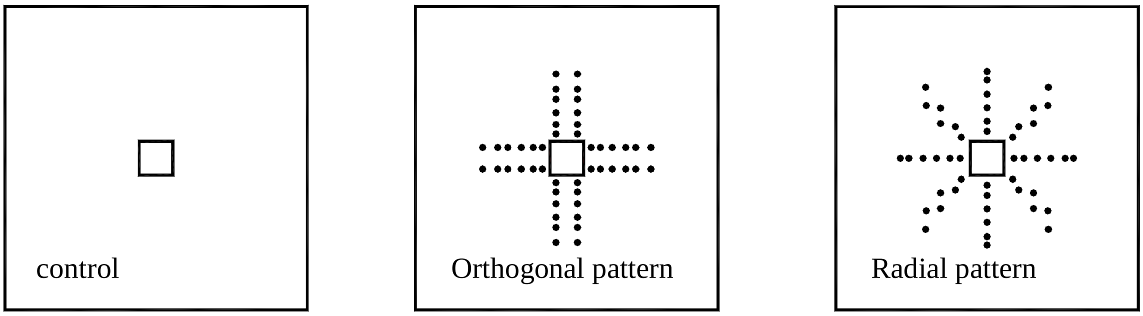


Fig. 3. Examples of shear bolt patterns used in the experiments

5. Slab-Column Interior Connections

Specimen SB1 had no shear bolts while SB2, SB3 and SB4 had two, three and four peripheral rows of 9.5 mm diameter shear bolts (8 bolts in each row), respectively. Specimens SB5 and SB6 both contained four rows of shear bolts and also had openings (70×70 mm) placed next to the columns. The slabs were tested in a displacement control mode.

Figure 4 shows the central deflection for all specimens recorded by the internal LVDT of the top loading actuator. The observed displacements showed improved ductility with the increase in the number of shear bolts. Specimen SB2 reached its flexural capacity and failed immediately after by punching outside the shear reinforced zone. Specimens SB3 and SB4 yielded at peak load (flexural failure) and then sustained large post-peak deflection at constant load, until final punching failure of the slab occurred outside the shear reinforced zone. Ductility, calculated as the ratio of the deflection at the first yield of flexural reinforcement to the ultimate deflection, was found to increase with the number of shear bolts (Table 1). Slabs with openings (SB5 and SB6) also reached their flexural capacities, and then allowed for some post-peak deflections until punching occurred through the shear studs. At this point the slabs did not break but continued to allow deflections with the reduced load capacity of the connection. These results show that failures occurring in the shear-reinforced zone are ductile.

6. Slab-Column Edge Connections

Tests on slab-columns edge connection with shear bolts (6 specimens) are compared to specimens without shear reinforcements, XXX, SF0 and their identical counterparts, XXX-R and SF0-R with 9.5 mm diameter shear studs (six peripheral rows placed during construction) [5], [6]. Details regarding the specimens are given in Table 1 and in [1]. SF0, SF0-R and SH-2SR had an opening (150×150 mm) immediately in front of the column. The shear bolts were manufactured from 12.7 mm diameter rods.

All specimens were subjected to a constant M/V ratio of 0.3. The results are presented in Figure 5. Table 1 shows that shear reinforcement in slabs increases strength and ductility of the connections. Shear studs prevented punching shear failures in both XXX-R and SF0-R. Shear bolts, applied to the existing hardened slabs, also prevented punching shear failures of the specimens by increasing their strength and ductility. The slabs reinforced with shear bolts had almost the same behaviour and strength as the slabs with shear studs. The shear-bolt reinforced slabs underwent larger post-peak deflections and rotations; however, since this testing was done in load control, it is difficult to quantify the post-peak ductilities. It can be however, observed that for both types of reinforcements the ductility of the connection is substantially increased in comparison with unreinforced specimens. The final crack pattern for the specimens SB1 and SB4 are shown in Fig 7

7. Interior connections under pseudo-seismic loads

1) Nine specimens were tested in this series (SW1 ~ SW9). Top horizontal lateral load versus top horizontal lateral drift ratio for SW1, SW2 and SW3 are shown in Figure 6. Significant differences exist between the responses of the specimens with and without shear bolts. The specimen without shear bolts, SW1, reaches the maximum moment of 69 kNm. The maximum moment was achieved at 2.85% drift after which the specimen failed by punching. Specimen SW2, which contained 4 rows of shear bolts, reached the maximum moment of 89 kNm at 6%

drift. SW3 (6 rows of shear bolts) reached also 89 kNm at 5.3% drift. After reaching the maximum load the specimen continued to deform with minimal loss of load bearing capability.

Table 1. Summary of experimental program on shear bolts at the University of Waterloo

Type	Name	Comments	Test Failure Load Vertical [kN] /moment [kNm]	Ductility (mm/mm)
Edge, static	XXX	Control, n.o.	125/38	4
	SF0	Control, openings	110/33	3
	SX-1SR	shear bolts, n.o., 1 row, s.p.	151/45	5.9
	SX-2SR	shear bolts, n.o., 2 rows, s.p.	155/47	12.4
	SX-2SB	shear bolts, n.o., 2 rows, s.p.	162/49	8.7
	SH-2SR	shear bolts, 1 opening, 2 rows, s.p.	141/42	6.1
	SX-GF-SB	shear bolts and FRP laminates on tension side, n.o., 2 rows, s.p.	170/51	8.2
	SH-GF-SB	shear bolts and FRP laminates on tension side, 1 opening, 2 rows, s.p.	162/49	6.4
Interior, static	SB1	Control, n.o.	253/0	1.0
	SB2	shear bolts, n.o., 2 rows, o.p.	364 /0	2.0
	SB3	shear bolts, n.o., 3 rows, o.p.	372/0	2.1
	SB4	shear bolts, n.o., 4 rows, o.p.	360/0	3.4
	SB5	shear bolts, 4 openings, 4 rows, o.p.	353/0	5.0
	SB6	shear bolts, 2 openings, 4 rows, o.p.	336/0	4.1
Interior, pseudo-dynamic	SW1	Control, n.o. P=110kN	110/69	2.1
	SW2	shear bolts, n.o., 4 rows, o.p. P=110kN	110/89	6.5
	SW3	shear bolts, n.o., 6 rows, r.p. P=110kN	110/89	6.6
	SW4	shear bolts, n.o., 6 rows, o.p. P=160kN	160/93	5.4
	SW5	shear bolts, n.o., 6 rows, o.p. P=160kN	160/78	2.6
	SW6	Control, 2 openings, P=160kN	160/53	-
	SW7	shear bolts, 2 openings, 6 rows, o.p. P=160kN	160/57	1.3
	SW8	shear bolts, 2 openings, 6 rows, r.p. P=160kN	160/64	1.0
	SW9	shear bolts, n.o. 6 rows, r.p. P=160kN	160/94	4.1

n.o. = no openings; r.p. = radial pattern; o. p. =orthogonal pattern, P = constant vertical load for pseudo seismic tests.

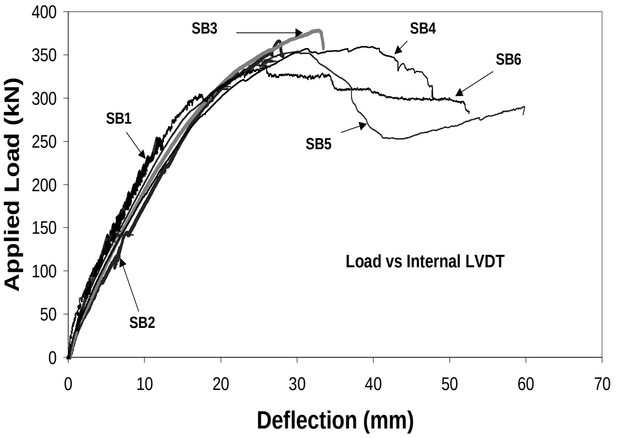


Fig. 4. Load versus central displacement for internal connection

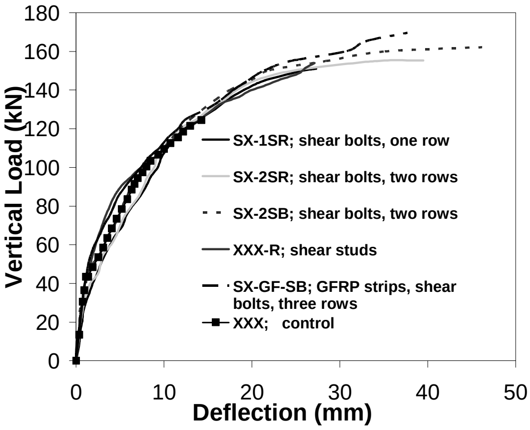


Fig. 5. Comparison of the vertical dimension of shear cracks for SB1, Sb2, SB3 and SB4

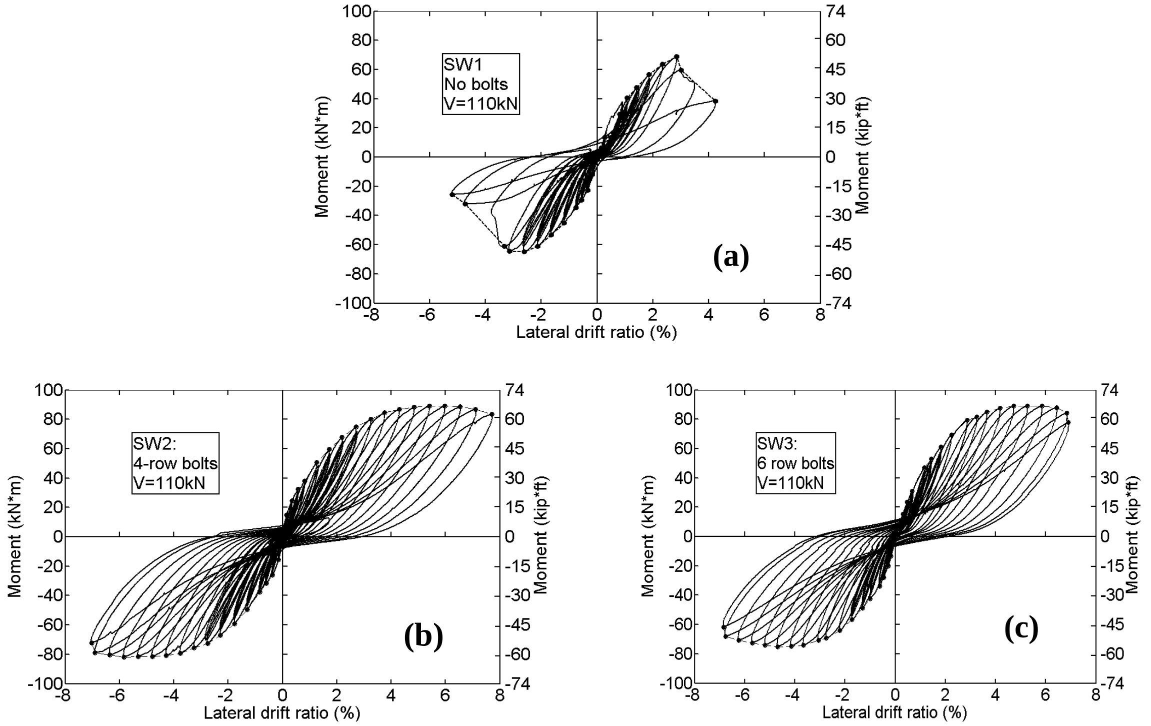


Fig. 6. Horizontal load vs. horizontal drift ratio at top column end.

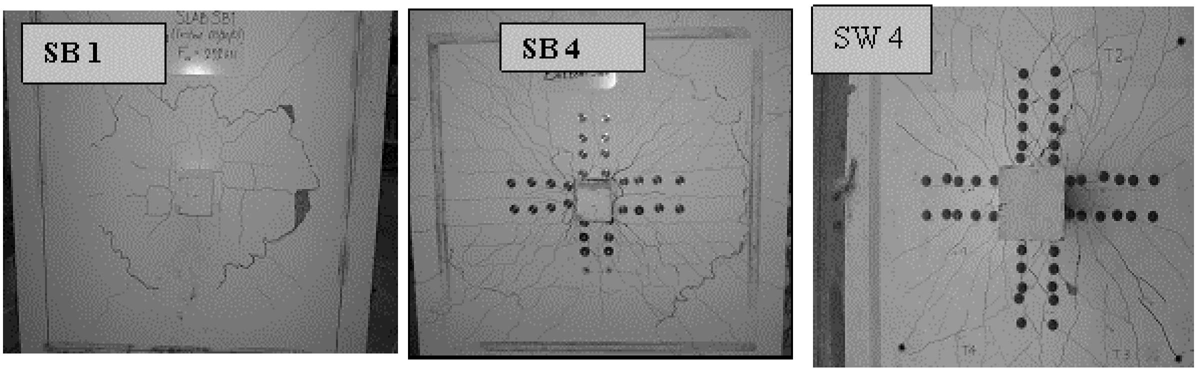


Fig. 7. Final crack patterns on tension side for SB1, SB4 with no openings and four rows of shear bolts and SB 6 with two openings and four rows of shear bolts

Peak drift ductility, defined as a ratio between lateral displacement at peak load and displacement at the first yield of longitudinal reinforcement, is shown in Table 1. All specimens with shear reinforcement experienced peak ductilities much larger than their counterparts without shear reinforcement. The final crack pattern for the specimen SW4 is shown in Fig 7.

8. Conclusions

The presented research shows that shear bolts can be effective as a method for punching shear retrofit of flat slabs subjected to static and seismic loads. Shear bolts provide means for changing the failure mode from punching to flexural. They increase both strength and ductility of the connection being at the same time simple and cost effective.

The method has a potential for practical field applications for strengthening of reinforced concrete slabs subjected to gravity, transverse and earthquake loadings. It can also be important for abnormal loading scenarios, which can trigger progressive collapse of the surrounding structure. Shear bolts may well serve to dwarf such devastating failure if appropriately retrofitted into existing flat slab structures.

References

1. El-Salakawy E., Polak M.A., Soudki K.: New Shear Strengthening Technique for Concrete Slabs. ACI Structural Journal, 100 (3)/2003, 297–304.
2. Adetifa B. and Polak M.A.:Retrofit of Interior Slab Column Connections for Punching using Shear Bolts. ACI Structural Journal, 102(2)/2005, 268–274.
3. Bu W. and Polak M.A.: Seismic Testing of Interior Slab-Column Connections Strengthened with Shear Bolts. ACI Structural Journal, in print, 2009.
4. Feld, J. and Carper, K. L.: Construction Failure. 2nd Edition, John Wiley & Sons, Inc./ 1997.
5. Carino N. J., Woodward K.A., Leyendecker E.V., Fattal S.G.: A Review of the Skyline Plaza Collapse. Concrete International, 5(7)/1983, 35–42.
6. Wood J.G.M.: Pipers Row Car Park, Wolverhampton, Quantitative Study of the Causes of the Partial Collapse on 20th March 1997 report **http://www.hse.gov.uk/research/misc/pipersrow.htm**
7. Rosenblueth E. and Meli R.: The 1985 earthquake: causes and effects in Mexico City. Concrete International, 1986.
8. Sabol T. A.: Flat Slab Failure in Ductile Concrete Frame Building. 1994 Northridge Earthquake, Case Study 1.13/1994, 167–187.
9. El-Salakawy E.F., Polak M.A., Soliman, M.H.: Reinforced Concrete Slab-Column Edge Connections with Shear Studs. Canadian Journal of Civil Engineering, 27/2000, 338–348.
10. El-Salakawy E.F., Polak, M.A., Soliman, M.H.: Reinforced Concrete Slab-Column Edge Connections with Openings. ACI Structural Journal, 96(1)/1999, 79–87. Wright R.N.:Fire and Building Research. NIST BSS 179/2003.