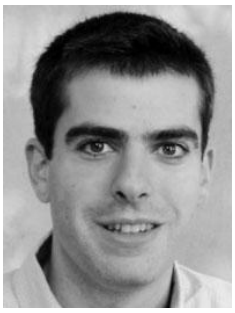
APPLICATIONS OF BENT-UP BARS AS SHEAR AND INTEGRITY REINFORCEMENT IN R/C SLABS



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Abstract

Bent-up bars were extensively used as shear reinforcement in beams and slabs from the first R/C developments up to the 1970's. Their use was justified by the fact that they allowed enhanced development of the tensile reinforcement at the same time they acted as shear reinforcement. New reinforcing bars (with reduced development lengths) in combination with shear reinforcing systems led however to the abandon on their use. Recently, interest has again grown on the use of bent-up bars in flat slabs. This is explained by their efficiency both as shear reinforcement (alone or in combination with stirrups) and as integrity reinforcement.

In this paper, the results of 7 full-scale specimens (3.0×3.0×0.25 m) reproducing the support region of an actual flat slab with different layout of bent-up bars are presented. The tests show different potential failure modes and allow understanding the contribution of this reinforcement to the shear-carrying capacity of the specimens. Additionally, the performance of bent-up bars as integrity reinforcement is discussed with reference to 9 half-scale specimens (1.5×1.5×0.125 m) where the influence of the development conditions of the bent-up bars is clearly assessed.

Keywords: Punching shear, Bent-up bars, Shear reinforcement, Integrity reinforcement, Critical shear crack theory, Flat slabs

1 Introduction

During the last century, bent-up bars were commonly used to increase the punching shear strength of flat slabs. The advantage was that they acted as flexural reinforcement while they also worked as shear reinforcement. Despite this advantage bent-up bars have been abandoned and have been replaced by other punching shear reinforcement systems such as double headed studs, stirrups, or shear steel heads because of their ease of construction. Consequently, most research on bent-up bars has been performed in the fifties and sixties of the past century and only few thereafter (Elstner and Hognestad (1956); Rosenthal (1959), Andersson (1963), and Hawkins (1974)).

However, nowadays interest of the use of bent-up bars has reappeared, yet not primarily as punching reinforcement but in combination with other punching shear reinforcement systems or as integrity reinforcement if no punching shear reinforcement is used. The objective in both cases is not only to increase the deformation capacity of the slab but also to reduce the risk of a brittle failure of the slab-column connection (**Fig 1**). Even if a local failure occurs, the bent-up bars behave as integrity reinforcement allowing the flat-slab to redistribute the loads to other columns

(as sufficient deformation capacity can be provided, **Fig. 1**) preventing a progressive collapse of the entire structure. This new consideration has also led to new research efforts, which focus mostly on the deformation capacity before and after punching failure (Broms (2006), Papanikolaou et al. (2005)).

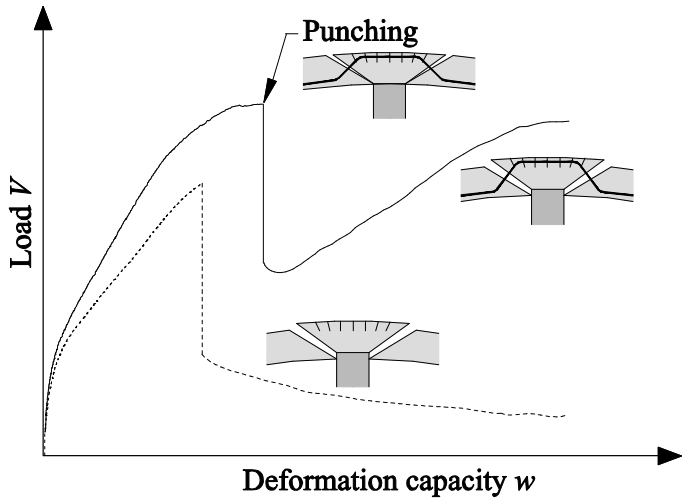

Fig. 1 Load-deformation curves with punching and post-punching behavior of slabs with and without bent-up bars

Under this new aspect two experimental campaigns concerning bent-up bars have been performed at the Ecole Polytechnique Fédérale de Lausanne. The first campaign (Tassinari et al. (2010)) investigated the punching behavior of slabs with bent-up bars with respect to the load-rotation behavior and to the activation of the bent-up bars for different failure modes that usually are governing: punching failure at the outer perimeter of the bent-up bars and punching failure with activation of the bent-up bars (**Fig. 2**). The second campaign (Mirzaei (2010)) investigated the behavior of the bent-up as integrity reinforcement.

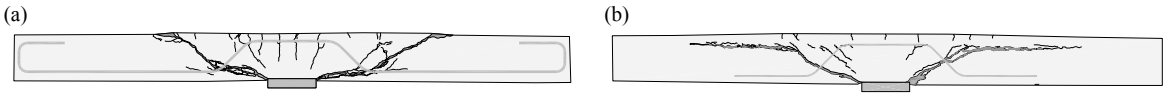

Fig. 2 Punching failure modes of slabs with bent-up bars: (a) failure outside bent-up bar (PT41) and (b) failure with activation of the bent-up bars (PT43)

2 Experimental campaign

The investigation consisted of two experimental campaigns on normal strength concrete (with concrete compressive strength measured on cylinder ranging between 32.8 MPa and 51.7 MPa). In the first test campaign (Tassinari et al. (2010)), 7 full-scale slab specimens have been tested to investigate the strength and the deformation capacity of the slab as well as the activation of the bent-up bars. The investigated parameters have been the flexural reinforcement ratio, the amount of bent-up bars, the inclination of the bent-up bars, and the anchorage length. Constant parameters have been the slab dimensions (3.0 x 3.0 x 0.25 m) and the column size (0.26 m). The second test campaign consisted of 9 half-scale slab specimens (Mirzaei (2010)). These slabs belong to an extensive research on the post-punching behavior of flat-slabs, which have been performed to investigate amongst others the behavior of slabs with bent-up bars used as integrity reinforcement. The investigated parameters have been the amount and the anchorage conditions of the bent-up bars. Constant parameters have been the slab dimensions (1.5 x 1.5 x 0.125 m), the column size (0.13 m), and the flexural reinforcement ratio. Measurements of the load deflection and slopes were taken for all tests (Series PT & PM). Additionally, measurements on strains at the bent-up bars

were performed for certain specimens (Series PT). Several representative load-deformation curves for the two types of tests are shown in **Fig 4**.

Tab. 1 Main parameters of the slab specimens

Specimen	ρ [%]	d_m [mm]	Bent-up bars	β_1 / β_2 [°]	f_{sy} [MPa]	f_{sby} [MPa]	f_c [MPa]	V_R [kN]	ψ_R [‰]	w_R [mm]
PG19	0.75	205	-	-	510	-	45.0	859	12.1	
PG20	1.50	201	-	-	551	-	51.7	1096	9.2	
PT41	0.80	200	2x3ø14 mm	45/0	510	550	50.8	1106	20.5	
PT42	1.57	200	2x3ø14 mm	45/0	551	550	51.7	1283	11.3	
PT43	1.61	195	2x3ø10 mm	45/0	578	526	38.2	1250	12.7	
PT44	1.61	195	2x2x3ø10 mm	45/0	578	526	43.0	1416	14.9	
PT45	1.61	195	2x3ø10 mm	30/0	578	526	38.3	1121	10.6	
PM3	0.82	102	-	-	601	-	37.8	324		13.1
PM13	0.82	102	2x2Ø8 mm	45/10	601	616	32.6	327		11.4
PM14	0.82	102	2x2Ø10 mm	45/10	601	560	32.7	356		12.6
PM15	0.84	100	2x2Ø12 mm	45/10	601	548	32.7	274		9.1
PM16	0.83	101	2x2Ø14 mm	45/10	601	527	32.8	298		10.1
PM17	0.82	102	2x2Ø8 mm	30/0	625	625	39.7	329		15.1
PM18	0.88	95	2x2Ø10 mm	30/0	625	605	39.8	323		15.7
PM19	0.85	99	2x2Ø12 mm	30/0	625	559	39.9	417		28.7
PM20	0.82	102	2x2Ø14 mm	30/0	625	578	40.0	402		19.3

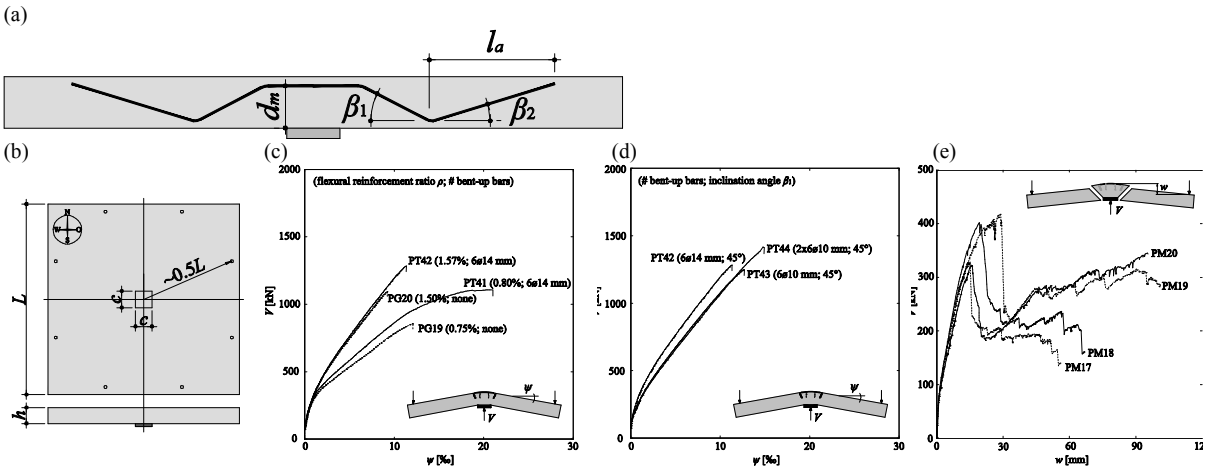

Fig. 3 (a) Definition of bent-up bars parameters; (b) geometry of the slab and load application; (c-e) load-displacement curves for tests on punching (c, d) and post-punching behavior (e)

3 Main results and conclusions

Based on the experimentally obtained results, the following conclusions are drawn:

1. The strength and deformation capacity of slabs with bent-up bars compared to slabs without bent-up bars can be significantly increased (PG19/PT41). Additionally, the flexural reinforcement can be decreased without losing punching strength, which leads to an even larger increase of the deformation capacity (PG20/PT41).
2. Various punching failure modes may develop, mainly failure at the outer perimeter of the bent-up bars and punching failure with activation of the bent-up bars. They have to be considered in design to obtain sufficient strength and a satisfactory post-punching behavior.
3. The proper consideration of detailing rules is essential in order to achieve significant increase in strength and deformation capacity. For example, a failure at the outer perimeter that would limit the strength and deformation capacity (PT42) can be prevented by using shifted bars (PT44) or a flatter inclination angle of the bent-up bars.

4. The anchorage conditions have a crucial influence on the performance of the bent-up bars. With respect to the punching tests (PT43-PT45), no anchorage failure could be observed despite the rather short anchorage length of 30ø for angles β_2=0°. With respect to the post-punching behavior (PM13-PM20), the anchorage of PM13-PM16 was clearly insufficient for values of β_2=10°. In these cases the performance could not be improved compared to slabs without bent-up bars, whereas the specimens with sufficient anchorage showed a significantly enhanced post-punching behavior.

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