Conclusions from tests on corbels

Autor(en): **Zeller, Wolfgang**

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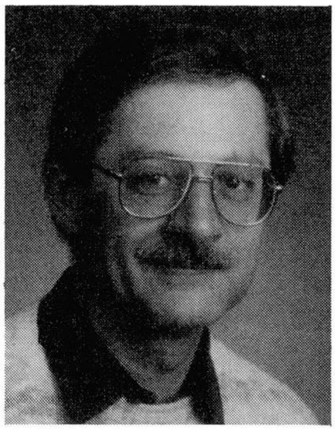
Conclusions d'essais sur des consoles courtes

Folgerungen aus Versuchen an Konsolen

Wolfgang ZELLER
Dipl.-Ing.
Univ. Karlsruhe
Karlsruhe, Germany



Wolfgang Zeller, born 1942, received his engineering degree from the University of Karlsruhe, Germany. Formerly he was concerned with prestressed concrete bridge construction in a consulting firm and later took up a position as a teaching assistant at the University of Karlsruhe. Presently, he is engaged in research on bridge bearings and corbels.

SUMMARY

Results of tests on reinforced concrete corbels are presented. Load-carrying behaviour after diagonal splitting is explained using a refined strut-and-tie model.

RÉSUMÉ

On présente les résultats d'essais réalisés sur des consoles courtes. Le comportement après la fissuration dans la bielle comprimée est discuté à l'aide d'un modèle de treillis modifié.

ZUSAMMENFASSUNG

Es werden Ergebnisse von Versuchen an Konsolen vorgestellt. An einem verfeinerten Fachwerkmodell wird das Tragverhalten nach dem Auftreten von Spaltrissen erläutert.

1. INTRODUCTION

Research on corbels has been an ongoing concern at the University of Karlsruhe since the early 1960's when Franz/Niedenhoff [1] suggested the simple strut-and-tie model to design reinforced concrete corbels. Tests in the late 1970's [2] have shown that heavily reinforced concrete corbels, with an a/d ratio of 1.0, require not only horizontal but, also, vertical stirrups to prevent failure caused by diagonal splitting in the compression strut. This is due to transversal tensile stresses. More recent tests described in this paper are concerned with investigating the behaviour of the compression strut and the stirrup reinforcement used for different corbel designs.

2. TESTS

Two double corbels with a/d ratios of 0.5 and 1.0, respectively, were loaded to failure (Fig. 1). The tension reinforcement A_s consists of horizontal loops, having equal cross sections for both specimens. Horizontal stirrups were used for corbels K1 to K3 to carry the transverse tensile stresses present in the compression strut. These had an amount of reinforcement equal to 1/3, 1/2 and 1/3 respectively, of the reinforcement A_s. Vertical stirrups were arranged in corbel K4 to resist the transverse tensile stresses. Steel reinforcement strains and concrete strains were measured with electrical resistant strain gauges. Table 1 gives details of the corbel design and failure loads.

Failure modes

Corbel K1 : The horizontal stirrup reinforcement first yielded and deformed extensively after the formation of wide inclined cracks, followed by crushing of the concrete in the compression strut at the column corner. Stresses in the ties were below the yield limit. A special device was then used to strengthen this corbel before the adjoining corbel K2 could be tested to failure.

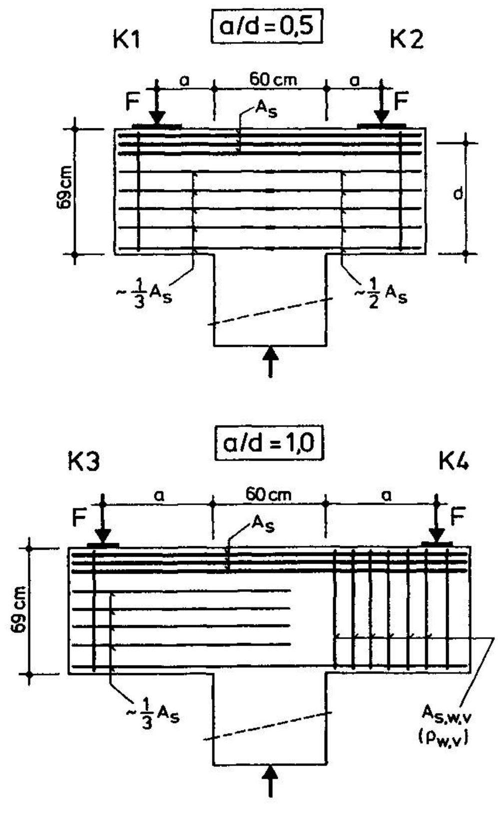


Fig. 1 : Corbel details: reinforcement and dimensions

Corbel No		K 1	K 2	K 3	K 4	units
Ratio	a/d	0,5		1,0		-
Span	a	30		60		cm
Effective depth	d	60		60		cm
Width	b	30		30		cm
<u>Steel</u>						
Tension	A_s	15,5		15,5		cm^2
reinforcement	f_y	~500		~500		N/mm^2
	ρ_l	0,86		0,86		%
Stirrups	A_{swh}/A_s	~1/3	~1/2	~1/3	-	-
(horizontal)	ρ_{wh}	0,38	0,55	0,39	-	%
Stirrups (vertical)	ρ_{wh}	-	-	-	0,37	%
<u>Concrete</u>	f_c	24,5		22,5		MN/m^2
<u>Failure</u>	F_u	948	>1000	455	683	kN
	$\tau_u = F_u/bd$	5,26	>5,55	2,53	3,79	MN/m^2
	τ_u/f_c	0,215	>0,227	0,112	0,169	-

Tab. 1: Experimental test results

Corbel K2 : A maximum load of 1000 kN was reached before the strengthened corbel K1 failed once again. At this load level the stresses in the horizontal stirrups of corbel K2 were just below the yield limit of the steel. The concrete strains in the compression zone at the column corner reached values greater than 4 $^{o}/_{oo}$, suggesting that this corbel would not be able to carry much higher loads.

Corbel K3 : Failure occurred suddenly by diagonal splitting of the compression strut. This was immediately followed by concrete crushing in the zone at the column corner.

Corbel K4 : This corbel failed progressively by crushing of the concrete in the compression zone after extensive yielding of the tension reinforcement (flexural tension failure). Most of the vertical stirrups also exceeded their yield limit.

Crack development
Vertical flexural cracks in the column area began to appear first at very low load levels. These cracks were followed by the formation of inclined cracks at higher load levels and then diagonal splitting cracks which developed near the bearing plate and propagated into the compression zone. The splitting crack widths were geater than those of the flexural cracks. Fig. 2a shows a typical crack pattern of specimen K3 /K4.

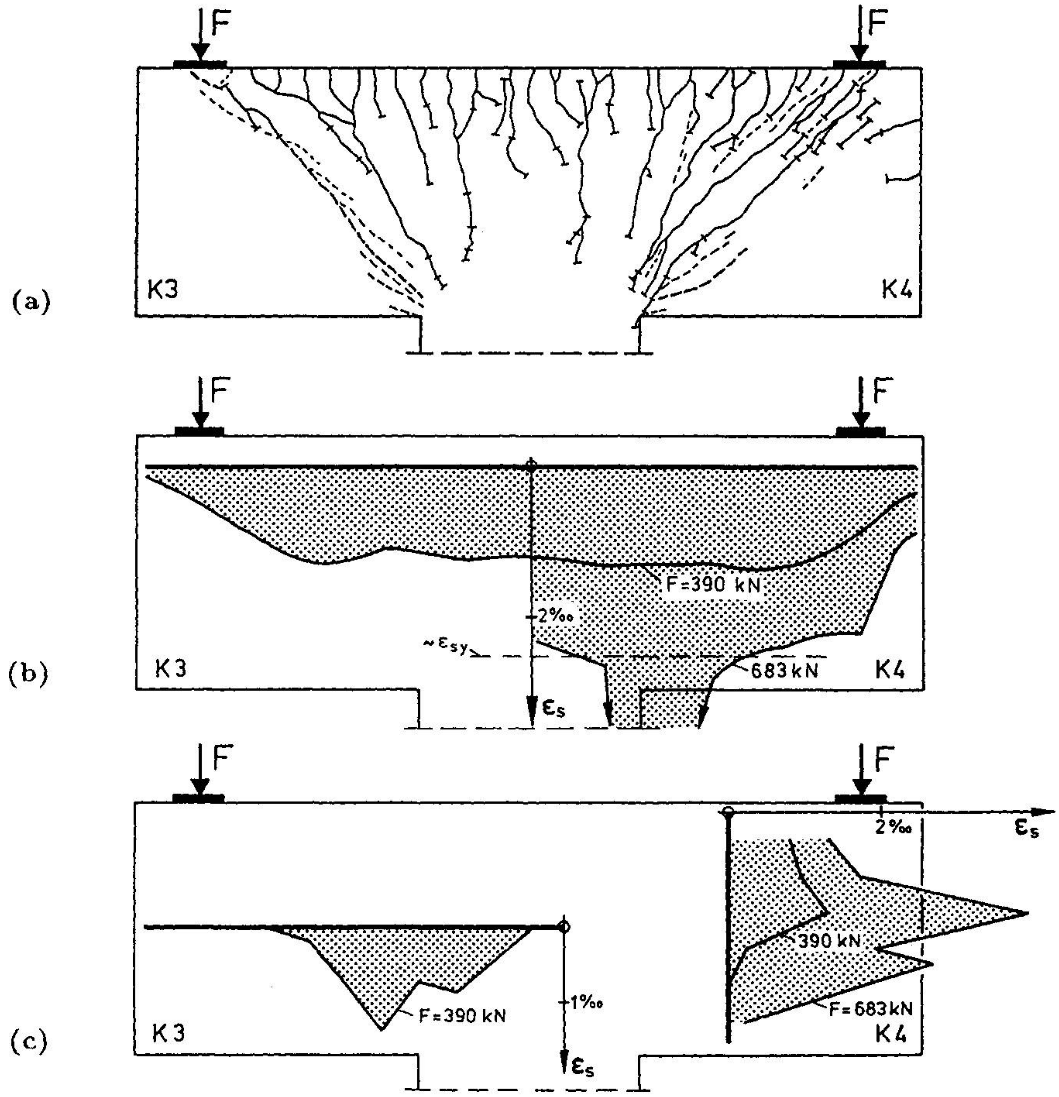


Fig. 2 : Corbels K3 and K4 (a/d = 1.0) : (a) crack pattern; (b) and (c) strain distribution in the tie reinforcement and in both a horizontal and vertical stirrup

Strain measurements

The distribution of the tension tie reinforcement was fairly uniform between the two load bearing plates for corbels K1/K2. However, this was not quite the same case for specimen K3/K4 (Fig. 2b). The maximum strains in both the vertical and horizontal stirrups always occurred in the compression strut area where the bars crossed the splitting cracks (Fig. 2c).

The distribution of concrete strains and stresses is shown in Fig. 3. Stresses are determined from the measured strains and a uniaxial cylinder stress-strain response exhibiting strain softening. Stresses in the compression struts were greatest at the column corner.

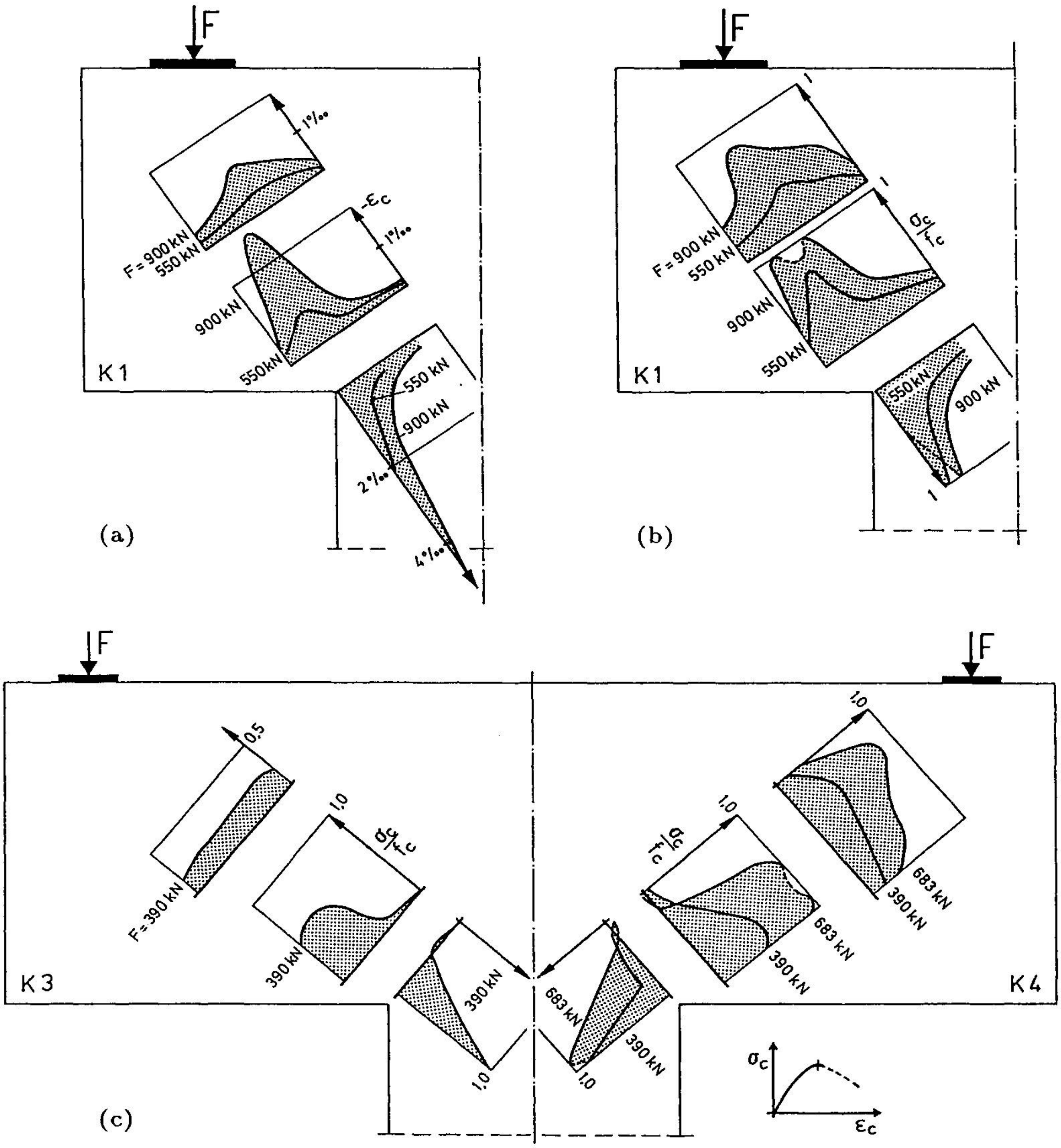


Fig. 3 : Concrete compression strain and stress distribution in corbels K1 and K3/K4

3. DISCUSSION

Results from tests on the corbels demonstrate that stirrups are needed to account for the tranverse tensile forces which develop in the compression strut. The horizontal stirrups used in corbel K1 ($a/d = 0.5$) were not sufficient to prevent crushing of the concrete in the column corner because of extensive yielding in the stirrups. The same behaviour is assumed for corbel K2. Recall that the stirrup reinforcement used in these corbels was equal to either 1/3 or 1/2 of the tension tie reinforcement. The horizontal stirrups used in corbel K3, having a larger aspect ratio $a/d = 1.0$, were not very effective, while the vertical stirrups used in corbel K4 resulted in a much higher failure load. The flexural tension failure observed for this corbel was caused by yielding of the tension reinforcement. Hence, corbels should be designed with enough vertical stirrups to allow for this type of failure.

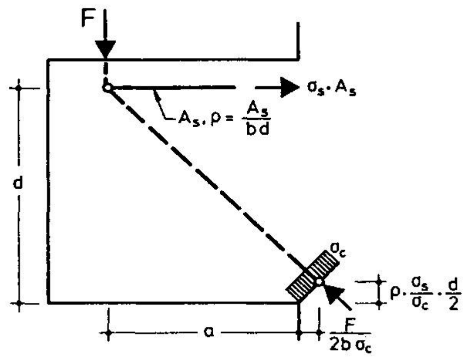


Fig. 4: Simple strut-and-tie model

The simple strut-and-tie model (Fig. 4) is not useful when diagonal splitting occurs. Fig. 5 shows a refined model which is able to analyse post-crack behaviour up to failure. Behaviour at the column corner is only considered since failure should always happen here if the loading node is properly detailed. Rotations occur primarily as a result of deformation in both the tie and transverse tension strut. Rotation on side 1 is greater than that of side 2. Since the struts are not really pinned at the column node, rotation is restrained and consequently strains are greater on side 1. Hence, tensile tie and stirrup reinforcement influence the strains in strut 1 by affecting the rotation of the system. The concrete strains obviously increase greatly when the tranverse tension strut begins to yield, resulting in failure of the concrete.

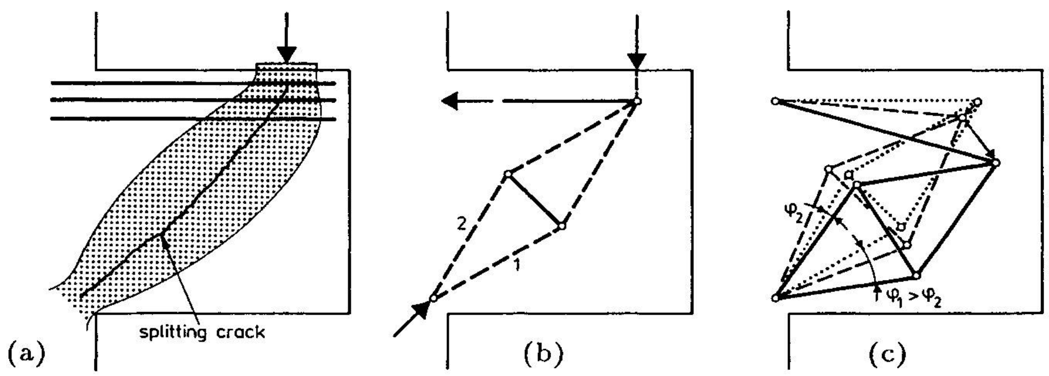


Fig. 5 : Strut-and-tie model explaining diagonal splitting; (a) bottle compression field; (b) refined model; (c) deformation and rotation

Further theoretical research has shown that the magnitude of the tensile splitting force depends on (1) the width of the compression strut at the column corner node and (2) the dimension of the bearing plate and depth of the tension main bars at the loading node.

The width of the compression zone is influenced by the amount of the tensile and the splitting reinforcement. Additionally, the splitting force increases with larger a/d ratios and is not proportional to the force in the main tension bars, as commonly suggested. This assumption leads to an amount of tensile splitting reinforcement which is too small, especially for corbels whith a small a/d ratio.

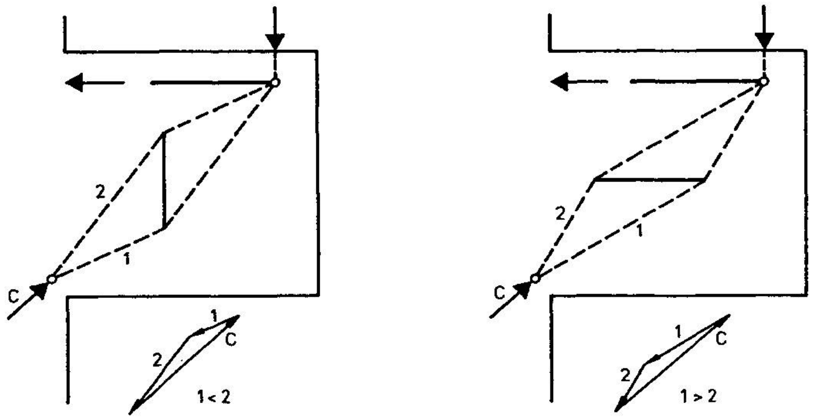


Fig. 6: Strut-and-tie models for corbels reinforced with horizontal or vertical stirrups

The amount of stirrup reinforcement also increases when the orientation of this reinforcement differs from the splitting tensile force vector which is approximately perpendicular to the direct compression strut. In this case, vertical stirrups are more sufficient when the angle of the compression strut is lower than 45°. Conversely, horizontal stirrups are better when the angle exceeds 45°, as is the case for corbels with a/d ratios smaller than about 0.7 to 0.9. Fig. 6 illustrates that when the direction of the splitting reinforcement deviates from the tensile force vector, then not only the splitting forces change but, also, the compresson forces in the column corner.

The tests and analysis described in this paper have shown that the bearing capacity of corbels is greatly influenced by the arrangement of the splitting tension reinforcement, and that the simple strut-and-tie model was not able to account for the actual stresses in the compression zone after diagonal splitting occurred.

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