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Transverse Tension Decisive for Compressive Resistance of Concrete Cover

Importance de la tension transversale pour le résistance en compression du recouvrement de béton

Querzug massgebend für Mitwirkung der Betondeckung in der Druckzone

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SUMMARY
To ensure the durability of reinforced concrete members, concrete cover has been increased lately. This paper shows that the strength of members may be reduced by an increasing concrete cover because this often leads to a higher transverse tension in the concrete cover of the compression zone, for example in frame corners subjected to positive moments and in beams subjected to shear and bending.

RÉSUMÉ
On montre qu'un accroissement du recouvrement de béton – pour des raisons de durabilité – peut entrainer une réduction de la résistance de certains membres du fait d'une augmentation de la tension transversale dans la zone de béton en compression. Cela peut ainsi réduire de façon notable la résistance à la rupture dans des angles soumis à des moments positifs.

ZUSAMMENFASSUNG
In diesem Beitrag wird aufgezeigt, dass die aus Gründen der Dauerhaftigkeit erhöhten Betondeckungen die Tragfähigkeit von Bauteilen negativ beeinflussen können, da die Vergrösserung der Betondeckung in vielen Fällen höhere Querzugbeanspruchungen in Betondruckzonen hervorruft. Dies gilt z.B. bei Rahmenecken mit an der Innenseite Zug erzeugender Biegebeanspruchung und bei Balken, die auf Schub und Biegung beansprucht sind.

1. INTRODUCTION

Concrete cover is usually regarded today as a perfect part of the compression zone. In general a sufficient tensile strength of concrete must be presupposed to do so.

A change of direction of the compressive stresses in frame corners subjected to positive moments as well as a change of magnitude of the compression force in beams with acting shear reinforcement causes tensile stresses in the concrete cover of the compression zone.

But all common codes allow omission of these tensile forces.

In the cases mentioned before a biaxial stress state exists. It must be considered that with increasing longitudinal compressive stress the transverse tensile strength is decreasing /1/. Our design rules were derived from laboratory tests, which were carried out with preciseness avoiding temperature shocks; therefore it is to be expected that in these tests the tensile strength was much higher than in practice. Furthermore most of these tests were made with a very thin concrete cover (1.0 - 2.5 cm), which is smaller than the concrete cover claimed by codes to ensure durability (Table 1).

Member	Exposure Class	DIN 1045 59	DIN 1045 72/78	DIN 1045 88	MC 78	MC 90	EC2 90	
Slabs	interior	10	10	20	15	20	20	[mm]
	humid	15	20	30	20	35	25	[mm]
	humid de-icing	<40	30	50	30	50	40	[mm]
Beams	interior	15	15	20	15	20	20	[mm]
	humid	20	25	35	25	35	30	[mm]
	humid de-icing	<40	35	50	35	50	45	[mm]

Table 1 Comparison of the concrete cover for different codes (nominal values)

In this paper some examples will show that the influences mentioned above can lead to safety risks even when the requirements of the codes are fulfilled.

2. FRAME CORNERS WITHOUT INCLINED REINFORCEMENT

Extensive laboratory tests of frame corners without inclined reinforcement subjected to positive moments were performed by Nilsson /2/ and Kordina /3,4/. Especially in cases of higher reinforcement ratios failure occured far below the calculated ultimate moment. The calculated ultimate moment was determined at an even beam for the same reinforcement. The reason for failure is generally a spalling of concrete cover or of the outer part of the compression zone in that area, where the compression force is being diverted. Afterwards the resisting

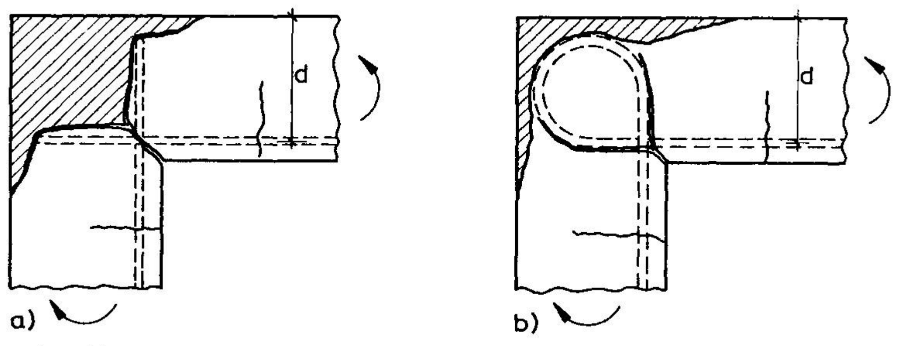

Fig. 1 Graphical illustration of the failure for two different tests of corners subjected to positive bending moments (and two different types of reinforcement)

moment decreases abruptly. Already under a small load a crack begins to form at the inside of the corner. Under higher load the crack divides into two cracks which approximately follow the reinforcement until the tensile force, which is necessary for diverting the compression force, cannot be carried any more and failure occurs. For example see the two crack patterns in Fig.1.

The force distribution in the corner can be described simplified by means of a strut and tie model /5/, which takes into account the failure mechanism and therefore separates the forces in the concrete cover /6/. See Fig.2.

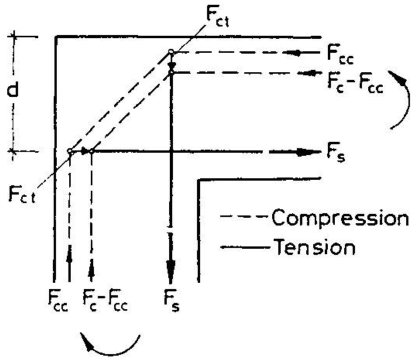

Fig. 2 Strut and tie model illustrating the failure mechanism.

This simple model shows that the compressive force F_{cc} of the concrete cover can only be diverted by the tensile Force F_{ct} resulting from concrete tensile stresses. The compressive force F_{cc} has to be determined with an area A_c, the height of which must exceed the concrete cover c, because the crack area between the reinforcement bars is curved (Fig.3). In this paper the area A_c is determined simplified by $A_c = b \cdot c' = b \cdot (c+s/4)$ with c = concrete cover and s = distance of the bars. The approximation s/4 means that the crack area assumed to be a parabolic area with a maximum inclination of 1.5:1.

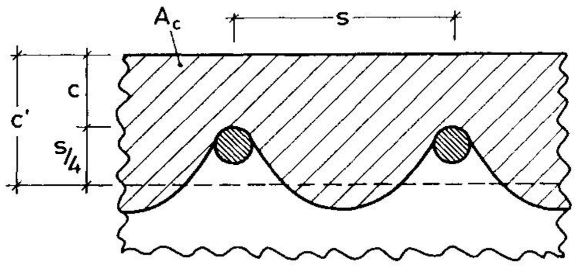

Fig. 3 Area A_c for the determination of the compression force F_{cc} of the concrete cover.

Taking into account the fast increasing of F_{cc} with increasing concrete cover for a given bending moment it is evident that also the tensile stresses which are decisive for the failure, grow fast. If in case of a small concrete cover the tensile strength is already utilized, it is obvious that in case of a larger concrete cover an equilibrium is only possible if a reduction of the bending moment occurs.

The German code DIN 1045 allows the design of frame corners subjected to positive bending moments without inclined reinforcement up to a reinforcement ratio $\mu = 0.4$ %. It must be pointed out, that a limitation of μ is not a good criterion but that a limitation of $\omega = \mu \cdot f_s/f_{ct}$ (a mechanical reinforcement ratio referred to the tensile strength of concrete) would be more precise.

In case of reinforcement ratios $\mu < 0.4$ % and normal concrete strength the influence of the concrete cover in the range of $2cm \leq c \leq 5cm$ at the compression zone is without much importance for members with small depth ($d \leq 20$ cm), because the neutral axis depth x for the calculated ultimate moment is not much higher than c'(for c = 2 cm). But in case of members of intermediate height ($d \sim 50$ cm)the influence of the concrete cover (at the compression zone) on the resistance may be great.

Taking, for example, a member with $\mu = 0.4$ %, B 35 (DIN 1045)$\cong$ C 30/37 (EC2), d = 40 cm and s = 8 cm, an increase of the concrete cover from c = 2 cm to c = 5 cm causes an increase of F_{cc} of about 25 %. Assuming that for a concrete cover c = 2 cm the resistance due to the transverse tension is already met, so that no greater F_{cc} can be carried, the failure moment is about 17.5 % lower. Taking into account the influence of the longitudinal compressive stress on the transverse tensile strength acc. to /1/ the failure moment is still about 10 % lower, because the longitudinal stress at the distance c' from the edge is decreasing with increasing c' (in case of a depth of d = 60 cm the failure moment is for c = 5 cm about 14 % lower than for c = 2 cm, taking the changing tensile strength into account). The ultimate moments calculated from a regular design for bending of the cross section remaining after spalling is for d = 40 cm lower than, and for d = 60 cm almost equal to the failure moment in case of the spalling of the concrete cover. That means that in cases of higher cross-sections the calculated ultimate moment at the face of the corner for the cross-section remaining after spalling is higher than the moment when the concrete cover spalls. But it is possible, too, that for high cross-sections the failure moment is lower than the calculated one of the remaining cross-section in the face of the corner, because of excessive damage of the corner area during spalling of the concrete cover (compare Fig.1a).

3. FRAME CORNERS WITH INCLINED REINFORCEMENT

Tests showed that the failure of frame corners with inclined reinforcement occurs in a different way from the failure of corners without inclined reinforcement /2,3/. Fig. 4 presents examples for typical failure in case of additional inclined reinforcement. Failure does not start anymore at the face of the corner as shown in Fig.1 but at the area of the anchoring of the inclined reinforcement. The reorientation of the compression force of the concrete cover already takes place in this area and the resulting transverse tension leads to failure. In cases of corners with inclined reinforcement the failure moment was usually greater than the calculated ultimate moment in the face of the corner (neglecting the inclined reinforcement). Tests were carried out only up to rein-

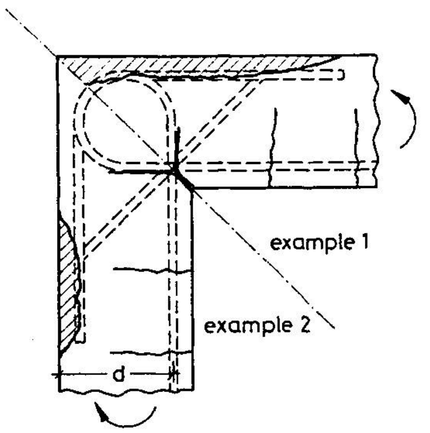

Fig. 4 Graphical illustration of failure of corners with inclined reinforcement subjected to positive bending moments

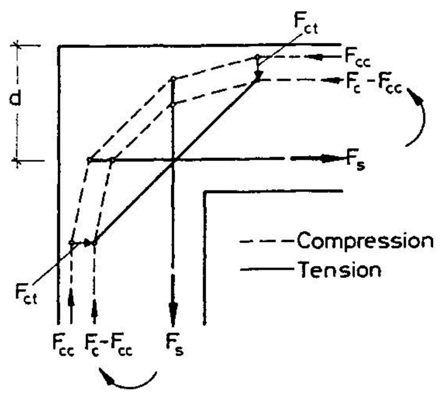

Fig.5 Strut and tie model, illustrating the failure mechanism

forcement ratios of μ = 1.1 %. All test specimen were reinforced in a way that failure should be initiated by flow of the reinforcement but it was observed in all tests that the failure was caused by spalling of the concrete cover in the area of the anchoring of the inclined reinforcement. The strain of the longitudinal reinforcement at failure amounted to about 2 ‰

A simplified strut and tie model presented in Fig.5 clearly shows the failure mechanism. The compression force F_{cc} of the concrete cover is already diverted in the area of the anchoring of the inclined reinforcement (activated for the sake of compatibility). The area of the face of the corner which is decisive for the failure of corners without inclined reinforcement, is relieved.

In the following the test V4 of Kordina is used as an example. The ratio of the failure moment to the calculated ultimate moment for pure bending was 1.0 (due to a normal force in tests the failure moment related to the axis of the tension reinforcement must be used). In the test specimen concrete cover was 2 cm. In case of a concrete cover of 5 cm the failure moment was calculated in accordance with chapter 2 by comparing the forces F_{cc}, in view of the influence of the compressive stress on the transverse tensile strength. The calculated ultimate load for the cross section remaining after spalling is of about the same size as the moment when the concrete cover spalls. The reinforcement ratio ot the test V4 was μ = 0.86 %. But the decisive value of μ corresponding to the compressive force F_c < F_s is only μ = 0.76 %, because a tensile axial force was acting on the cross-section. When the reinforcement ratio is related to the tensile strength of concrete, it becomes evident that this test in relation to all other tests of /2,3/ is among the most reinforced ones.

Taking into account that the tensile strength in practice is usually lower than in laboratory tests it is to be expected that in practice failure moments are lower, too. In corners with inclined reinforcement failure moment will increase moderately with increasing reinforcement ratio, because the cross section, which remains after spalling of the concrete cover will become decisive provided that the compression zone in the corner is not damaged too much.

4. BEAMS SUBJECTED TO BENDING AND SHEAR

Along a beams with high shear there is a rapid change of the compressive force. This means that there is also a rapid change of the compressive force F_{cc} in concrete cover; for example see the area close to the point of zero moments (Fig. 6).

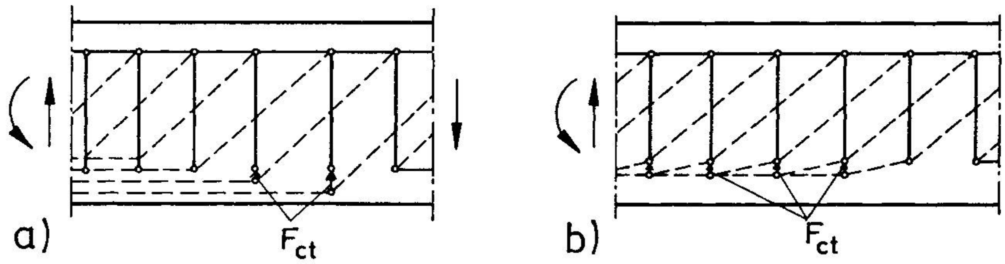

Fig. 6 Two Models illustrating a possible force distributions in a beam under high shear in the area close to the point of zero moments.

The model in Fig. 6a produces in case of thick concrete cover average transverse tensile stresses σ_{ct} = τ. Further on it will be shown that the model in Fig.6b causes smaller tensile stresses.

The force distribution in the compression zone for model Fig. 6b was examined for different concrete covers computing the compression zone as a wall. The influence of the thickness of the concrete cover was examined for the most unfavourable case of a beam with a overall depth of 30 cm (effective depth of 25 cm) and with a compression zone heigth of 10 cm. The compression field was supposed to act under an angle of 45° and to be uniformly distributed along the upper rim of the wall. The spacing of the stirrups was assumed to be 10 cm. Furthermore it was supposed that the transmission of the stirrup force into the wall-segment should cause constant forces along the length x-c", where c" = c + ϕ_s = c + 1 cm. Linear and constant distribution of the compressive stresses were examined, the resulting transverse tensile stresses differed only slightly. All calculations are based on a linear elastic behaviour of the material. For a concrete cover of c = 1 cm (c"= 2 cm) the average tensile stress amounts to about 9 % of the assumed acting shear stress τ. For a thick concrete cover c = 5 cm (c" = 6 cm) the calculation showed destinctly higher average tensile stresses of even more than 40 % of τ. Localized tensile stresses are even considerable higher.

This simplifying analysis shows that beams with a thick concrete cover which are substantially subjected to shear may reach an ultimate limit state by a spalling of the concrete cover. To what extent these theoretical results are representing the actual behaviour in the concrete cover should be checked by future tests.

5. SUMMARY

This paper deals with the negative influence of the increase of concrete cover upon the resistance of reinforced concrete. In codes the concrete cover was enlarged in the sake of the durability of concrete structures.

The influence of an increase of concrete cover on the transverse tensile stresses was examined in the case of a corner (with and without inclined reinforcement) subjected to positive bending moments. It was shown theoretically that an increase of concrete cover often leads to a substantial increase of the transverse tensile stresses in concrete. This causes also a substantial decrease of the failure moment compared with members with smaller concrete cover.

Also in cases of beams with high shear the transverse tensile stresses in the concrete cover of the compression zone increases considerably with increasing concrete cover.

The authors think that experimental research is urgently necessary to clarify the negative influence of an increasing concrete cover on the resistance of reinforced concrete.

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