Shear Strength of Beams at Very Low Temperatures

Résistance à l'effort tranchant de poutres à très basses températures

Schubtragfähigkeit von Stahlbetonbalken im Tieftemperaturbereich

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SUMMARY

Loading tests on 14 reinforced concrete beams were performed both at ambient temperature and at −165°C. Most beams failed in shear. From the results, it follows that under cryogenic conditions shear strength increases considerably. This effect is mainly due to the increase of concrete tensile strength at low temperatures. Also restrained thermal shortening of the reinforcing steel has a beneficial effect.

RÉSUMÉ

Une série de 14 poutres en béton armé a été soumise à un essai de mise en charge et ceci à températures ambiantes et à −165°C. La plupart des poutres présentent une rupture à l'effort tranchant. Les résultats des essais montrent que la résistance à l'effort tranchant augmente considérablement en environnement cryogénique. Ce phénomène peut être attribué principalement à l'augmentation de la résistance à la traction du béton à basses températures. La contraction thermique empêchée de l'acier à également un effet favorable.

ZUSAMMENFASSUNG

An einer Reihe von insgesamt 14 Stahlbetonbalken wurden Schubversuche durchgeführt, sowohl bei Umgebungstemperatur als auch bei −165°C. Die meisten Balken erwiesen einen Schubbruch. Aus den Versuchsergebnissen folgt, dass die Schubtragfähigkeit erheblich zunimmt im Tieftemperaturbereich, was hauptsächlich am günstigen Einfluss der niedrigen Temperaturen auf die Betonzugfestigkeit zugeschrieben werden kann. Auch die verhinderte thermische Dehnung des Betonstahls hat einen günstigen Einfluss.

1. INTRODUCTION

Knowledge of the structural behaviour of concrete members at very low tempera-
tures is particularly important for the design of storage tanks for liquefied
natural gas (LNG). In the case of LNG tanks with elevated base slab (e.g. at
Zeebrugge, Belgium) the area around the supporting columns has to be checked
for punching shear not only under regular but also under accidental loading
conditions involving cooling of the slab from above due to spill from the
inner steel container. Also the wall to base connection is an area subjected
to important shear forces. Hence the need to investigate the influence of very
low temperatures on shear resistance of reinforced concrete beams and slabs.
In this paper, the results of loading tests on beams are discussed by addres-
sing the influence of low temperatures on material properties and by conside-
ring the action effects caused by internal restraints. As pointed out by Breen
[1], particular types of loading and restraints are among the technical chal-
lenges that remain to be explored. Moreover, shear strength is one of the
typical fields where reliance on concrete tensile strength is taken into ac-
count, as indicated by Hillerborg in [2].

2. TEST PROGRAM

Loading tests were performed on 14 reinforced concrete beams with a span of
1.5 m, a width b = 400 mm and a total depth h = 200 mm (fig. 1). The effective
depth d equals 165 mm and the tensile reinforcement of the beams consists of
deformed TEMPCORE bars Ø 14 mm. The beam designation (table 1) consists of the
capitals P (preliminary), R (reference) and L (low temperature) followed by
the longitudinal reinforcement ratio ρ_s = A_s/bd in % and the web reinforcement
ratio ρ_{sw} = A_{sw}/bs also in % (s denoting stirrup spacing). The stirrups con-
sist of 4 legged closed stirrups, 6 or 8 mm in diameter. By way of example,
the dimensions and the reinforcement of beams R/1.86/0.20 and L/1.86/0.20 are
shown in fig. 1.
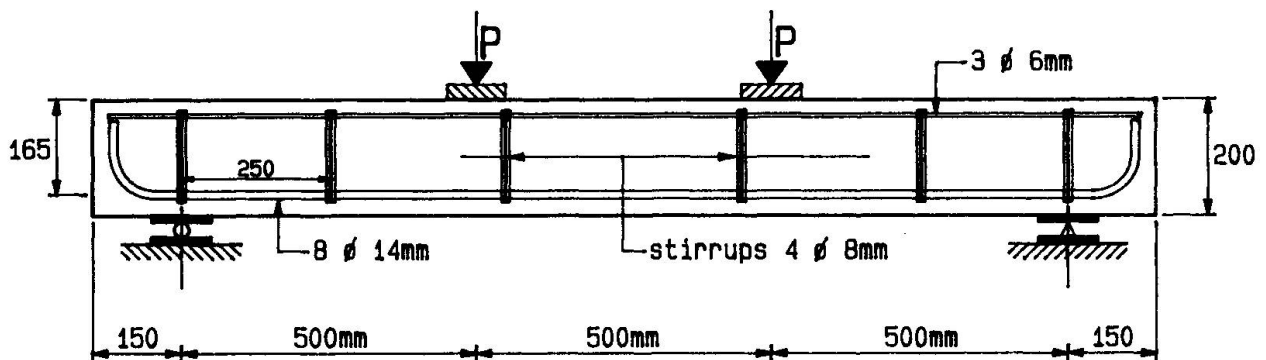
Fig. 1 Dimensions and reinforcement of beams R/1.86/0.20 and L/1.86/0.20

The beams designated P and R were tested at room temperature (20°C) at an age
of respectively 28 days and 3 months. The upper face of the beams designated L,
was cooled with liquid nitrogen (-196°C) until, at the level of the tensile
reinforcement, a temperature of about -165°C was reached. This latter value
corresponds to the temperature of liquefied natural gas. Cooling took about 6
hours. Subsequently the loads were gradually increased up to failure. Vertical
copper strips, partially embedded in the beams' upper surface, served to re-
tain the liquid nitrogen. Insulating pannels were glued at the side faces, in
order to obtain a uniform temperature distribution over the width of the beams.

Beam designation	ρ_s (%)	ρ_{sw} (%)	s (mm)	P_u (kN)	τ_u (N/mm²)	Type of failure
P/0.93/0.00	0.93	0	-	105	1.59	shear
P/1.86/0.00	1.86	0	-	122	1.85	shear
R/0.93/0.00	0.93	0	-	107	1.62	bending
R/0.93/0.19	0.93	0.19	150	108	1.64	bending
R/1.40/0.00	1.40	0	-	120	1.82	shear
R/1.86/0.00	1.86	0	-	136	2.06	shear
R/1.86/0.20	1.86	0.20	250	201	3.05	shear
R/1.86/0.34	1.86	0.34	150	195	2.95	bending
L/0.93/0.00	0.93	0	-	150	2.27	shear
L/0.93/0.19	0.93	0.19	150	189	2.86	bending
L/1.40/0.00	1.40	0	-	194	2.94	shear
L/1.86/0.00	1.86	0	-	278	4.21	shear
L/1.86/0.20	1.86	0.20	250	315	4.77	shear
L/1.86/0.34	1.86	0.34	150	275	4.17	shear

Table 1 Survey of beam characteristics

Fig. 2 Kani's shear failure valley [3]
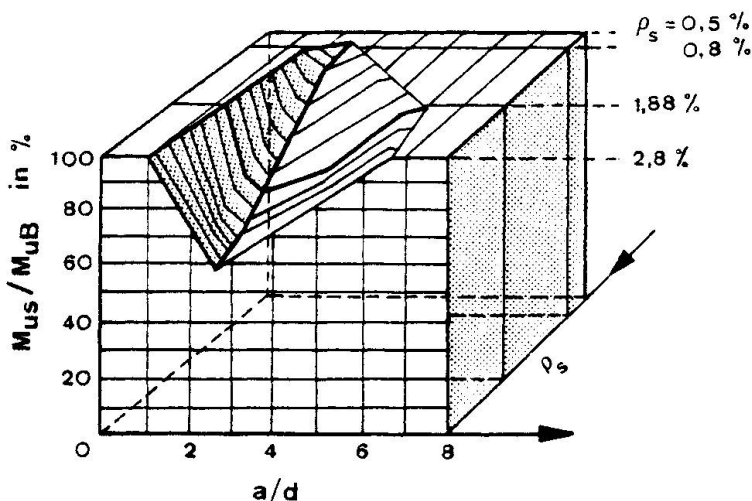
The beams were submitted to two point loads at a third of the span. Hence the shear span "a" equals 500 mm and a/d = 3. This latter value is known to be the most critical for shear strength [3]. In fig. 2 Kani's "shear failure valley" for beams without shear reinforcement is shown [3]. The diagram depicts the influence of a/d and ρ_s on the ratio of the ultimate moment corresponding to shear failure (M_{uS}) to the ultimate moment for bending failure (M_{uB}).

Stirrup spacing s = 150 mm corresponds to z/s = 1, where z = 0.9 d equals the depth in the equivalent truss model. In the case of s = 250 mm, the ratio z/s equals 150/250 = 3/5 which is the lower value of the crack inclination θ allowed in the "accurate" shear design method according to the CEB-FIP Model Code for Concrete Structures (1978 Edition).

3. MATERIAL PROPERTIES

The beams and the accompanying test specimens were cured in a moist room at 20°C until 24 hr before testing. Mean concrete strength characteristics are given in table 2. Due to the low temperature effect, compressive strength $f_{c,cub}$ increased by a factor 1.78 and flexural tensile strength f_{ctb} by a factor 1.49.

Beam type	28 days	3 months					
	$f_{c,cub}$	$f_{c,cub}$		f_c	f_{ct}	f_{ctb}	
	20°C	20°C	-165°C	20°C	20°C	20°C	-165°C
P	63.4	70.7	-	-	-	-	-
R	62.2	70.8	-	62.8	3.53	8.53	-
L	-	72.0	128.0	61.9	4.50	8.75	13.08

Table 2   Concrete strength characteristics in N/mm^2

For the longitudinal tensile reinforcement f_y = 504 N/mm^2 and f_{st} = 588 N/mm^2 were obtained as mean values at 20°C. For the type of reinforcing steel used it was found in previous research programs that the yield stress at -165°C increased by about 50 % compared to the value at 20°C [4]. However, calculated ultimate moments for the beams considered indicate that in this case the increase might be about 70 %. The ratio f_{st}/f_y approaches 1 under cryogenic conditions.

4. TEST RESULTS

The ultimate loads P_u and the type of failure are mentioned in table 1. Shear failures occured due to flexure shear cracking in the shear spans. For all beams, included those failing in bending, the nominal shear stress τ_u = V_u/bd is indicated in table 1.

5. DISCUSSION OF TEST RESULTS

5.1. General analysis

Comparison of the τ_u-values for similar beams failing in shear both at 20°C and -165°C, yields ratios varying between 1.43 and 2.04. This increase in shear resistance must mainly be attributed to the increase in tensile strength of the concrete due to the low temperatures (see also section 5.2).

The observation that for two identical beams, P/0.93/0.00 and R/0.93/0.00, the first fails in shear and the latter in bending can be explained by the fact that the value of ρ_s corresponds to the onset of Kani's shear failure valley (fig. 2). Hence, due to the scatter inherent to this type of test, either failure mode is equally likely to occur. However, at low temperatures, the shear failure mode is clearly predominant. The presence of stirrups in beam L/0.93/0.19 is not apparent form the failure load since beam L/0.93/0.00 failed already in bending.

Beam R/1.86/0.20, failing in shear, was probably already very near to the transition from shear to bending failure as beam R/1.86/0.34 fails at a slightly lower load in bending. At low temperatures shear failure is predominant for ρ_s = 1.86 %. The difference in web reinforcement ratio for the three beams L/1.86 is not reflected in the failure loads. Probably the onset of yielding of the tensile reinforcement initiated shear failure.

According to [3], the stirrups become active from a value τ_{oD} = 0.24 $\sqrt{f_{c,cub}}$ on. For beam R/1.86/0.20 this corresponds to a shear force 0.24 $\sqrt{70.9}$ x 0.9 x 165 x 400 = 120 kN. This value is in very good agreement with the experimental

strain measurements. These also indicate yielding of the stirrups at ultimate and hence the corresponding force equals $F_{sw} = f_y \times A_{sw} = 472 \times 201 = 95$ kN. Summation of both contributions yields 215 kN as estimate of the experimental value of 201 kN.

5.2. Influence of tensile strength on shear resistance

The influence of tensile strength on shear resistance is accounted for by a factor $\sqrt{f_c}$ in the formulas for the ultimate nominal shear stress. According to [3] the nominal shear stress for beams without stirrups is given by

$$\tau_{u,1} = 0.18 \sqrt{f_{c,cub}} \sqrt[3]{100 \, \rho_s} \tag{1}$$

for the particular values of the scale factor and a/d applicable to the beams considered. In [5], the following modification of the ACI 318 Building Code formula (11-6) was proposed

$$\tau_{u,2} = 0.15 \sqrt{f_c} + 62.6 \, \rho_s \, \frac{d}{a} \tag{2}$$

The calculated values are mentioned in table 3 and compared with the experimental values τ_u. For the cooled beams, the material properties at -165°C have been considered. Formulas (1) and (2) underestimate the experimental values by about 10 % and 25 % respectively, at least for the beams tested at 20°C and beam L/0.93/0.00. A better fit can be obtained for (1) by increasing the first factor up to 0.20 and for (2) by doubling the second term.

Beam	τ_u (N/mm^2)	$\tau_{u,1}$ (N/mm^2)	$\dfrac{\tau_u}{\tau_{u,1}}$	$\tau_{u,2}$ (N/mm^2)	$\dfrac{\tau_u}{\tau_{u,2}}$
P/0.93/0.00	1.59	1.41	1.13	1.33	1.20
P/1.86/0.00	1.85	1.75	1.06	1.51	1.23
R/1.40/0.00	1.82	1.67	1.09	1.49	1.22
R/1.86/0.00	2.06	1.79	1.15	1.56	1.32
L/0.93/0.00	2.27	1.99	1.14	1.78	1.27
L/1.40/0.00	2.94	2.28	1.29	1.88	1.56
L/1.86/0.00	4.21	2.55	1.65	1.97	2.14

Table 3 Experimental and calculated nominal shear stresses.

From table 3 it follows that for the lower temperatures and the higher ρ_s values the underestimation becomes very important which indicates that phenomena other than those accounted for by (1) and (2) must have a beneficial contribution to shear resistance.

5.3. Other phenomena affecting shear resistance at low temperatures

Under cryogenic conditions, the coefficient of thermal expansion of steel is only slightly reduced whereas that of concrete significantly decreases, depending on the moisture content. As pointed out in [4], the restrained differential shortening in a reinforced concrete section causes a kind of artificial prestressing. Considering a symmetrical section subjected to a uniform temperature drop ΔT, the compressive stress in the concrete can be calculated by the following formula

$$\sigma_c = \frac{E_s \cdot \rho \cdot (\alpha_{ts} - \alpha_{tc}) \cdot \Delta T}{1 + (\alpha - 1)\,\rho} \tag{3}$$

where α_{ts} and α_{tc} are the coefficients of thermal epansion of steel and concrete and ρ is calculated as $(A_s + A_{sc})/bh$. In the case of a non-symmetric reinforcement arrangement, this formula still holds for the stress at the centroid of the equivalent section $A_c + \alpha\,A_s$. Introducing $\Delta T = 190°C$, $E_c = 35000$ N/mm^2, $\alpha_{ts} - \alpha_{tc} = 3.10^{-6}/°C$ and the appropriate values of ρ, one finds $\sigma_c = 0.96$ N/mm^2 ($\rho_s = 0.93$ %), $\sigma_c = 1.36$ N/mm^2 ($\rho_s = 1.40$ %) and $\sigma_c = 1.74$ N/mm^2 ($\rho_s = 1.86$ %). The induced compressive stress σ_c has a beneficial influence on the principal tensile stress $\sigma_I = \sqrt{\sigma_c^2/4 + \tau_c^2} - \sigma_c/2$.

This effect is merely related to the first contributing term in (2) and does not fully account for the observed higher τ_u values at low temperatures and highest ρ_s values. The second term in (2), which reflects the influence of A_s, must also increase because of higher bond strength, and smaller crack widths and deflections at the same load level. These phenomena, confirmed by experimental observations, hamper propagation and opening of the inclined cracks.

6. CONCLUSIONS

From loading tests on reinforced concrete beams both at reference temperature (+20°C) and under cryogenic conditions (-165°C), it can be concluded that the beneficial effect of very low temperatures on shear strength has to be attributed to the following phenomena (in descending order of importance)
  - increased tensile strength of concrete
  - restrained thermal shortening of the steel, creating a kind of prestressing
  - higher bond strength and smaller crack widths, causing a higher contribution of the shear strength term proportional to ρ_s.

ACKNOWLEDGMENT

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