SHEAR CAPACITY OF PRESTRESSED EXTRUDED HOLLOW-CORE SLABS

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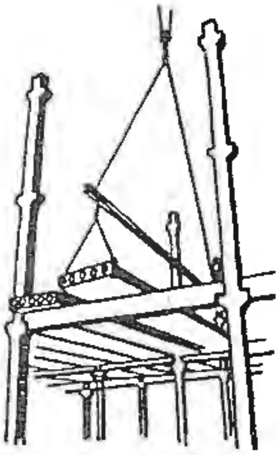


ABSTRACT

This paper reports the results of an experimental and theoretical study of the shear capacity of hollow-core slabs from two well known plants in Norway.
The purpose of this research was to study the behaviour of the slabs and the influence of the important parameters.
The full scale tests include 120 tests on slabs. The author has earlier carried out 114 tests on slabs of the same types.
The theoretical study is based on a linear elastic analysis and the computation is carried out with a finite element method. Solutions are derived for the shear capacity of the slabs at failure which take into account different cross-section shapes, the age of the concrete and the slip of the strands.
Finally the safety and the design capacity are dealt with.

Key-words: Hollow-core slabs, shear strength, precast concrete, Prestressing, Destructive tests, Experimental analysis, Theoretical analysis.

1. INTRODUCTION

Due to the very short support length and the strands which are sawn off at the end of the slabs, the extruded hollow-core slabs behave as unreinforced at the region near the support at failure. The only contribution from the reinforcement in this region is the compression from the prestressing. Therefore, it is of great importance to get accurate knowledge about the bearing strength of these types of slabs which are in widespread use. Because of the extruding the concrete differs from normally cast concrete.

2. TEST PROGRAMME

2.1 Test specimens, static system and test setup

Fig. 1 shows the slabs which are investigated. Additionally beams are sawn off from the slabs or wet cast and have shapes corresponding with the web with flanges to the centre of the cores. The measurements in all Figures are given in mm.

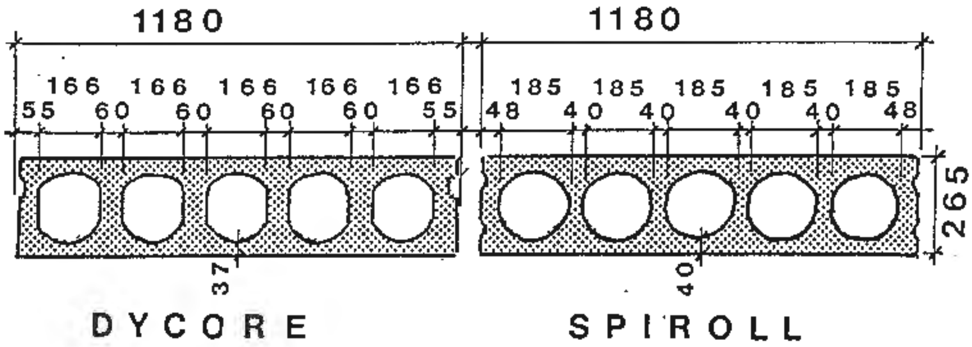


Fig. 1. Cross-section of the slabs produced by Østlandske Spennbetong a.s at Hønefoss and Precon a.s at Lillestrøm

The static system and the test setup are shown in Fig. 2. The most stressed support (A), with length 50 mm, was placed at the very end of the slab, which is considered the most unfavourable situation in practice.

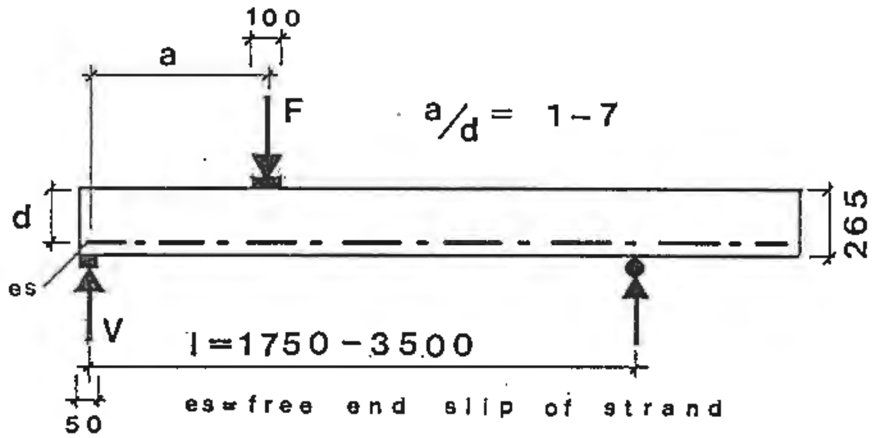


Fig. 2. Static system and test setup

The load beam and 2 hydraulic jacks were connected as shown in Fig. 3. The vertical deflection of the load beam was very small. When the total load F was 500 kN the max. deflection was only 0.3 mm.

2.2 Summary of the test programme

Type and number of specimens

The full scale tests include 120 slabs, 40 beams (one web) sawn off from slabs and 20 wet cast beams (same shape as the sawn off beams). In all 180 tests were carried out.

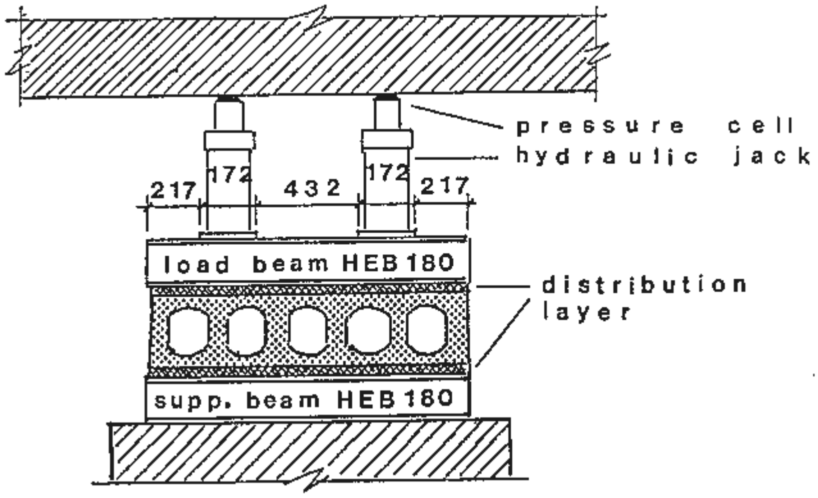


Fig. 3. Detail of loading and support

The compressive and splitting tensile strength were examined on 272 cylinder cores which were drilled from the slabs and beams. Additionally 41 wet cast cylinders and cubes were examined.

Intended quality:

First class, but not higher than normal

Main load:

Uniformly distributed knife load along the width of the slab

The intended variables were:

* Strand area A_S= 400, 700 and 1000mm²
* Strand diameter Φ= 12.8 mm (mainly) and 9. 5mm
* Ratio a/d= 1-7
* Degree of prestressing from 0-100 % (only wet cast beams)
* Concentrated loads and supports in some cases.

The unintended variables were:

* Concrete strength
* Free end slip of the strands
* Curing conditions,age before releasing the strands and age before cutting the elements in the factory
* Dimensions and surface(under load and on support)
* Age at the time of testing(had to be different because of the large number of tests)

2.3 Pressure distribution layer

To ensure the uniform distribution of the load and the support pressure, the following layers were used from the concrete surface of the slabs and beams:

Under the load:
1. Betokem Rapid mortar
2. Porous wood fibre plate 13 mm thick
3. Medium hard wood fibre plate 5 mm thick

On the support:
1. Porous wood fibre plate 13 mm thick
2. Medium hard wood fibre plate 5 mm thick
3. Pieces of sheet metal were pushed into the spaces between the surface of the support beam and the slab when necessary.

The bottom surface along the width of the slabs at the support region deviated more from the straight line than supposed. The maximum deviation was 1.5 mm for Dycore and 3.5 mm for Spiroll.

If the distribution layer is missing or does not work, the support pressure will be concentrated to some degree on one or more webs in the slabs. The concentrations are accidental and will cause scatter in the test results and the shear capacity will be reduced.

3. TEST RESULTS AND EXPERIMENTAL ANALYSIS

It is only possible to mention some of the results. Therefore, the most important results are reported here.

3.1 Knife load

The shear capacity V_u is distinctly influenced by the total area A_s of the strands, as shown in Fig. 4. The increasing of V_u is 14.6 % for Dycore and 12.3 % for Spiroll, when A_s increases from 700 to 1000 mm². The failure involved bending when A_s was equal to 400 mm² and was principal tensile when A_s was equal to 700 and 1000 mm². In each test the concrete tensile strength was decisive for the capacity of the slab. The coefficients of variation S were very small.

The range of S was 4.0 to 4.8 % for Dycore and 2.1 to 3.2 % for Spiroll.

The influence of the a/d-ratio and the value of A_s on V_u is shown in Figs. 5 and 6. The results of the experimental analysis are shown in Fig.6.

Design shear capacity

Based on the results which are shown in Fig. 6 and the safety coefficients for the different types of failure, the following conclusions are drawn for slabs with height h=265 mm:

A. Bending is the decisive mode of failure when the total strand area A_s is equal to 400 mm² or smaller.

The tensile strength of the concrete and the compression from the prestressing in the lowest flange govern the size of the capacity.

The anchorage capacity of the strands is too small to in crease the capacity after the first crack.

Consequently the tensile strength of the strands can not be utilized.

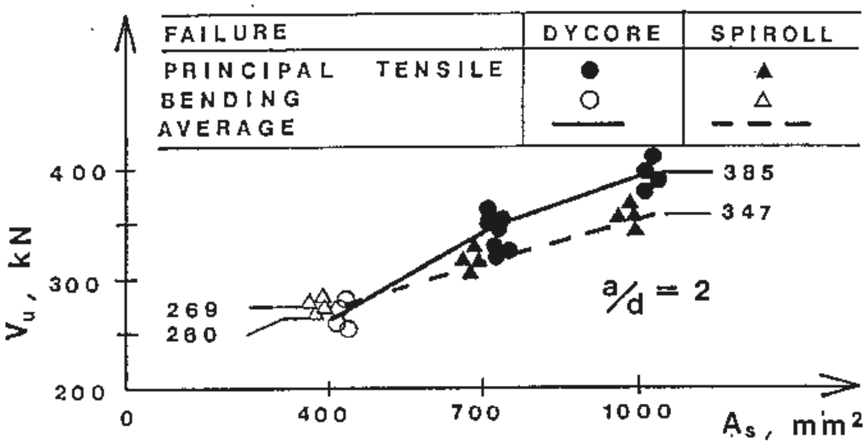


Fig. 4. Relationship between shear capacity V_u at failure and total area of strands A_s. Dycore and Spiroll with height h=265 mm and knife load along the width.

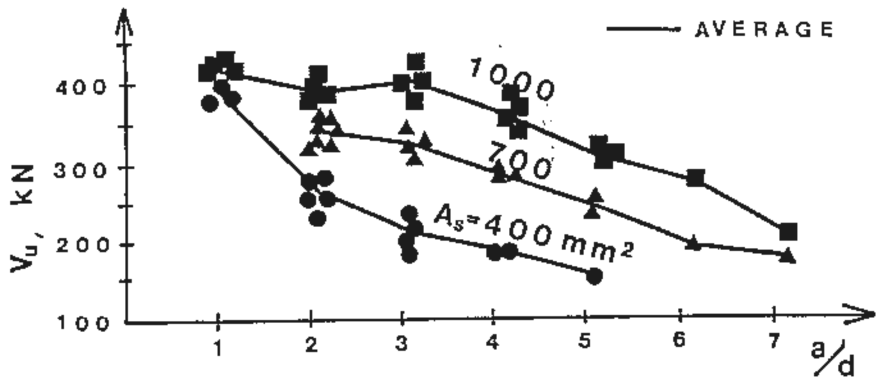


Fig. 5. Relationship between the shear capacity at failure V_u and the a/d-ratio. A_s = total area of strands. Dycore with height h = 265 mm and knife load along the width.

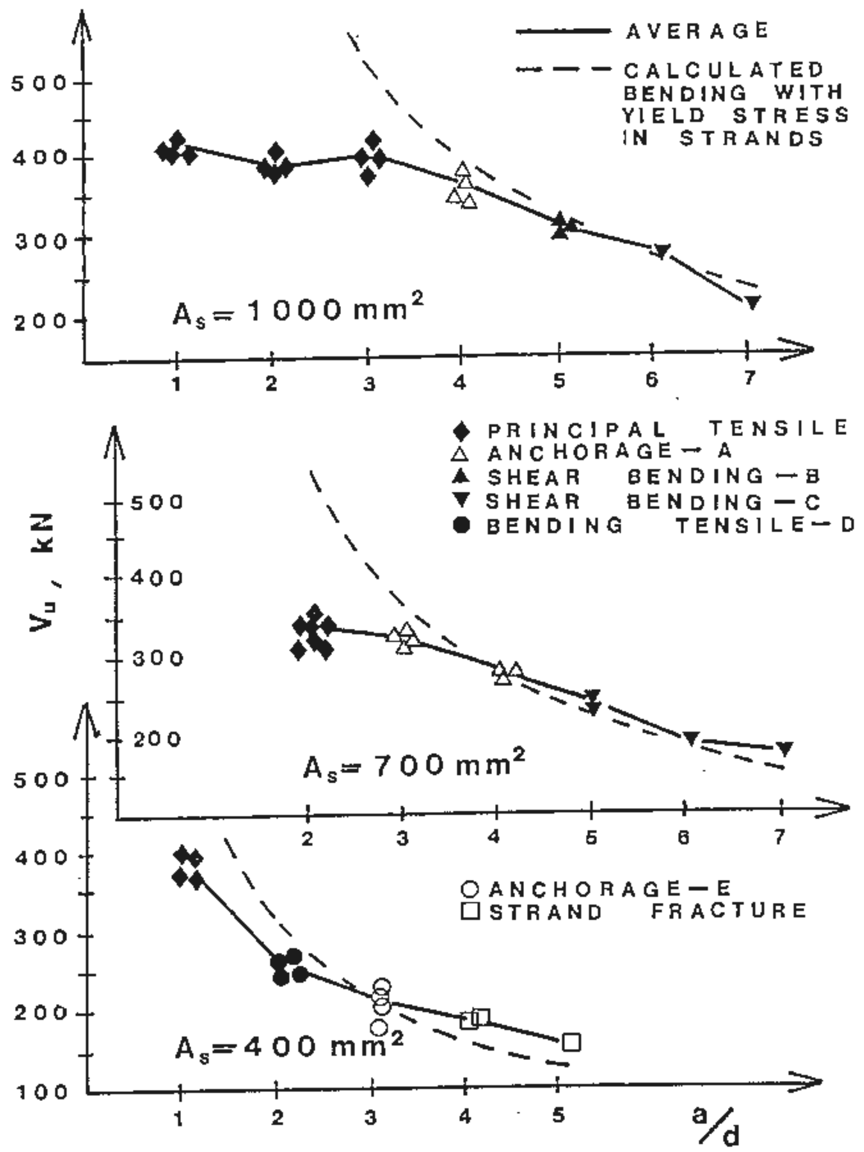


Fig. 6. Relationship between the shear capacity at failure V_u and the a/d-ratio compared with the calculated bending capacity. A_s = total area of strands. Dycore with height h = 265 mm and knife load along the width. The observed mode of failures are shown in the Figure with the following symbols:

A= from shear bending cracks B= anchorage/compression
C= compression D= concrete E= from bending cracks

B.

Principal tensile is the decisive mode of failure when the total strand area A_s is equal to 700 or larger.

The tensile strength of the concrete and the compression from the prestressing in the webs govern the size of the capacity.

The anchorage capacity of the strands is too small to increase the capacity after the first crack. Consequently shear bending can not occur near the support.

In the region between the support and the mid-span, shear bending may occur. However, shear bending is not decisive for the design capacity. The reason is that the coefficient of safety is much larger for principal tensile failure near the support than for shear bending failure between the support and the mid-span.

3.2 Concentrated load or support pressure

The shear capacity may be reduced considerably when the load or the support pressure is concentrated.
The capacity of support type D is larger than expected because the slab was separated along the length into 2 slabs which became new supports. But of course, the crack load was considerably lower for this type than for the other.

The widths in mm of the concentrated loads or supports along the width of the slabs in Fig. 7 were:

Type B: 228, C: 456, D: 145, E: 225, F: 145, G: 450

4. THEORETICAL ANALYSIS

Below this paper deals only with the problem of principal tensile, which is the most important mode of shear failure concerning these types of hollow-core slabs.

A knife load and a support pressure which are uniformly distributed along the width of the slab are investigated.

4.1 Distribution of the shear stresses on the webs

The real stress picture in the hollow-core slab is 3-dimensional and very complicated in the region near the support.

However, the usual way to calculate the principal tensile capacity is to add the smallest thicknesses of each web and regard the slab as one rectangular beam. The assumption is that the shear stresses in all the webs are equal.

When the support pressure is uniformly distributed along the width of the slab, which was the case in the main tests, the shear stress in the outer web of Spiroll is only 50 % of the stress in the inner web as shown in Fig. 8.

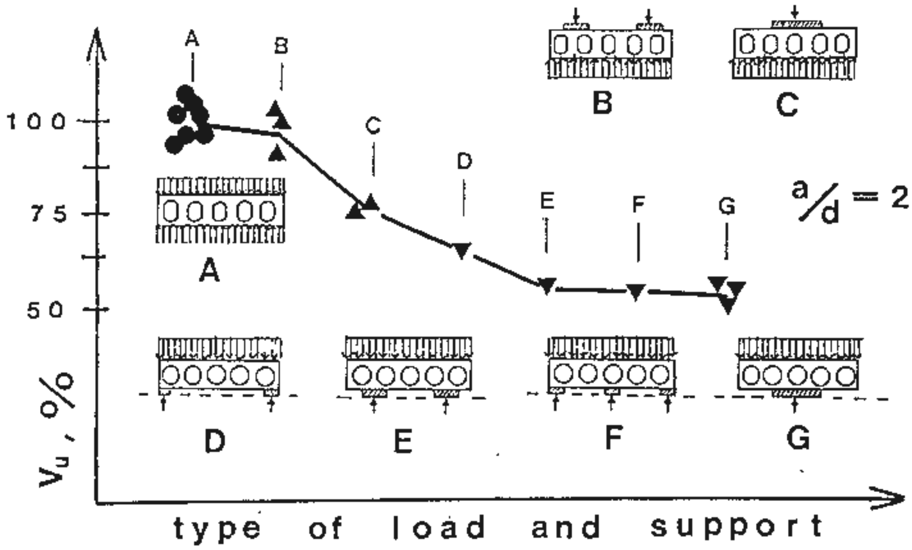


Fig. 7. Influence on shear capacity V_u at failure from concentrated load or support pressure along the width of the slab. Dycore and Spiroll hollow-core slabs with height h = 265 mm. The load or support is either concentrated or uniformly distributed along the width of the slab.

If the stresses in all the webs should be equal, the stiffness of the cross-section of the slab has to be larger than the stiffness of the webs from the support to the region where the max. principal tensile stress occurs.

The max. principal tensile stress occurs 180 mm from the centre of the support. Even 150 mm from the end of the slab the stresses are high, as shown in Fig. 12. Fig. 8 shows that even the stiffness of the cross-section between the outer and the inner web is smaller than the stiffness of the inner web from the support to the region where the max. principal tensile stress occurs. Hence the shear stresses in the webs can not be equal.

4.2 New calculation principle for hollow-core slabs

According to Sec. 4.1 the author propose to calculate the shear capacity (principal tensile failure) of hollow-core slabs with height h = 265 mm based on the following principle:

The weakest or most stressed web governs the capacity.If one or more webs are very weak,they should be neglected and the most stressed web of the remaining webs governs the capacity.

Normally the inner web with the lowest prestressing governs the shear capacity of Dycore and Spiroll with height 265 mm.

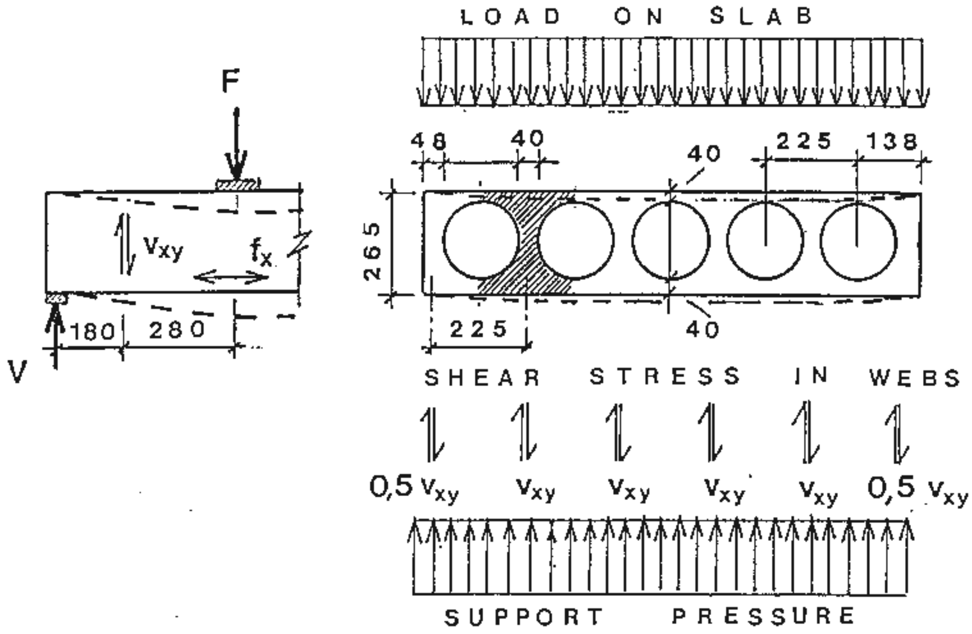


Fig. 8. Shear stress in the webs of Spiroll near the support when the load and the support pressure are uniformly distributed along the width of the slab.

The new principle makes it relatively easy to take into account the influence of the shape of the cross-section on the shear capacity. It is also possible to calculate the influence of concentrated loads or supports and blockouts in the slab.

4.3 Two-dimension linear elastic beam theory

The shear strength of a rectangular beam at half the height h, based on the principal tensile mode of failure, is given by:

$$v_{xy} = f_{ctu}(1+f_p/f_{ctu})^{0.5} \quad (1)$$

Eq. (1) is usually replaced by the approximate equation:

$$v_{xy} = f_{ctu} + 0.3f_p \quad (2)$$

The shear capacity is given by:

$$V_u = J/S\ b\ v_{xy} \quad (3)$$

For rectangular cross-sections Eq. (3) becomes:

$$V_u = 0.67\ v_{xy}\ b\ h \quad (4)$$

For one inner web with flanges to the centre of the cores in Spiroll and Dycore Eq. (3) becomes:

$$V_{wu} = 0.76\ v_{xy}\ b_w\ h \tag{5}$$

The Eqs. (5) and (2) give:

$$V_{wu} = 0.76(f_{ctu} + 0.3f_p)b_w\ h \tag{6}$$

4.4 Development of the prestressing force from the free end of the hollow-core slabs

The development of the prestressing force in the strand is shown in Fig. 9. The free end slip of the strand is given by:

$$es = 1/A_s*1/E_s\int_0^{l_t}(P_{so} - P_{sx})dx = P_{so}*l_t/2.5*1/E_s*1/A_s \tag{7}$$

With P_{so} = 120 kN, A_s = 100 mm² and $E_s = 2.1\ 10^5$ N/mm² the transmission length for one strand with diameter Φ=12.8mm is given by:

$$l_t = 438\ es \tag{8}$$

According to the US-code /2/ the transmission length is given by:

$$l_t = 64.4\ \Phi \tag{9}$$

The combination of Eqs. (8) and (9) give:

$$l_t = 34.2\ \Phi\ es \tag{10}$$

Eq. (8) and (9) are equal when es is equal to 1.36 mm.

4.5 FEM-analysis of the axial force from the prestressing

The relationship between the axial force P_{cx}, from the prestressing, on the concrete in the cross-section of the inner web in the slab and the distance x from the free end are shown in Fig. 10.

The influence of the free end slip es on P_{cx} is large.

The principal tensile stress f_1 is found to be max. at the distance 205 mm from the free end (Fig. 12).The influence of the free end slip es of the strand on P_{cx} is shown in Fig. 11. According to this figure the axial force in the cross-section where the max. f_1 occurs,is approximately given by:

$$P_{cx} = 0.39/es*P_{co} = 1/\Phi*5/es*P_{co} \tag{11}$$

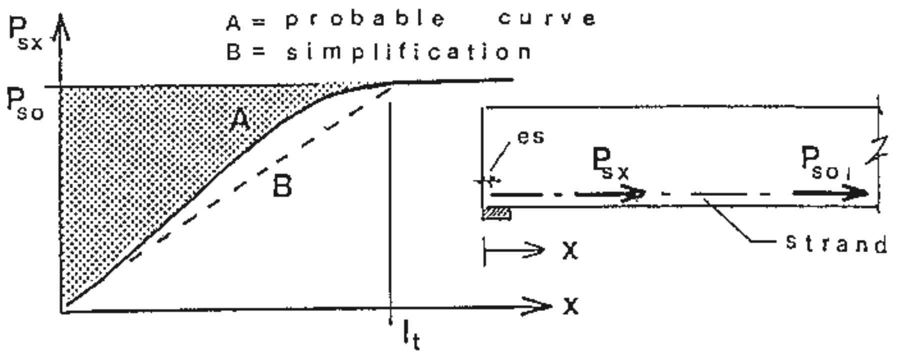


Fig. 9. Relationship between the prestressing force P_{sx} and the distance x from the free end. l_t=transmission length for the full prestressing force P_{so}. The curves are based on Ref. /8/.

P_{co} is approximately equal to P_{so} and Eq. (11) becomes:

$$P_{cx} = 1/\Phi*5/es*P_{so} \tag{12}$$

4.6 Compression in the cross-section from the prestressing

The sum of the losses of the prestressing force because of shrinkage, creep and steel relaxation is found to be 20 %. Hence the long time full compression force in the cross-section is equal to 0.8 P_{co}.
Consequently the compression in the cross-section of the inner web in the slab, from the prestressing, at the region with max. principal tensile stress is given by:

$$f_{pw} = 0.8P_{cx}/A_{cw} = 4/es*1/\Phi*P_{co}/A_{cw} = \tag{13}$$

4.7 FEM-analysis of the principal tensile stresses

Stresses in the cross-section of the inner web in the slab. Vertical load and prestressing and only vertical load.

According to Fig. 13 the following solution for the shear capacity is found to be more exact than Eq.(5):

$$V_u = k\ v_{xy}\ b_w\ h \tag{14}$$

with: k = 0.71 for Dycore and k = 0.91 for Spiroll

Eq.(14) gives 20 % higher values than Eq.(5) and 36 % higher values than Eq. (4), for Spiroll. The last corresponds very well with earlier tests, see Ref. /9/.

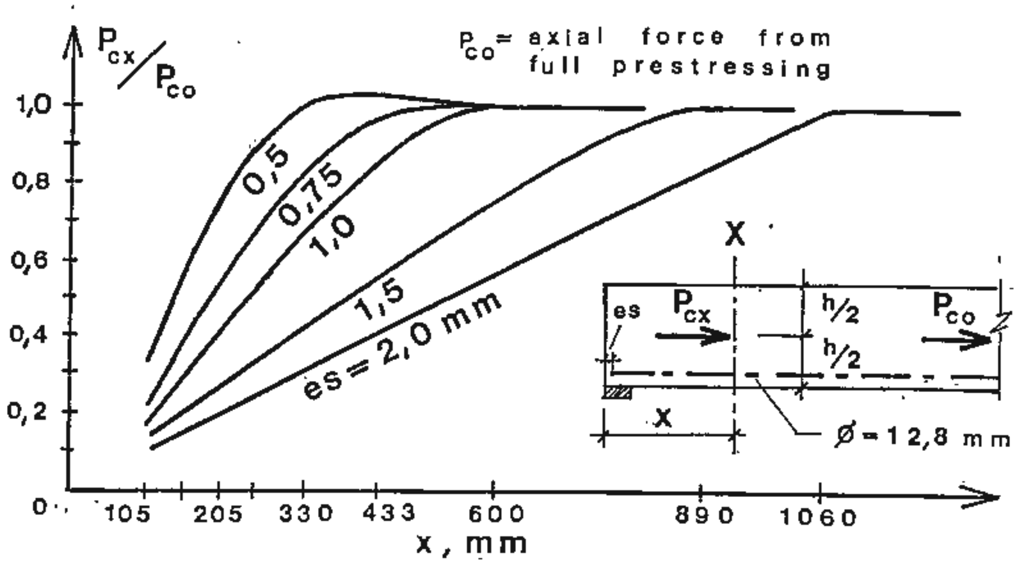


Fig. 10. Relationship between the axial force P_{cx} on the concrete (from the prestressing) and the distance x from the free end. Computed with FEM-analysis. The development of the prestressing force P_{sx} is based on curve B in Fig. 9.

5. CONCRETE TENSILE STRENGTH

The concrete tensile strength of extruded hollow-core slabs is quite decisive for the shear capacity. However, this strength is connected with many uncertainties because of the special method of production. The web thicknesses are also so small that the diameter of drilled cores has to be smaller than they should be.

The concrete tensile strength has therefore been investigated in particular by the author. The compressive and splitting tensile strength was examined on 272 cylinder cores which were drilled (most vertically) from the slabs and beams. Additionally 41 cast cylinders and cubes were examined. The fresh concrete in the cast specimens was equal to that which was used in the hollow-core slabs, apart from the admixture which was used in the cast specimens.

Some of the cylinders and cubes were also placed in a heating chamber with temperature 73°C for the first 2 or 5 hours. The purpose was to investigate the influence of heating the slabs. In the factories the slabs were heated.

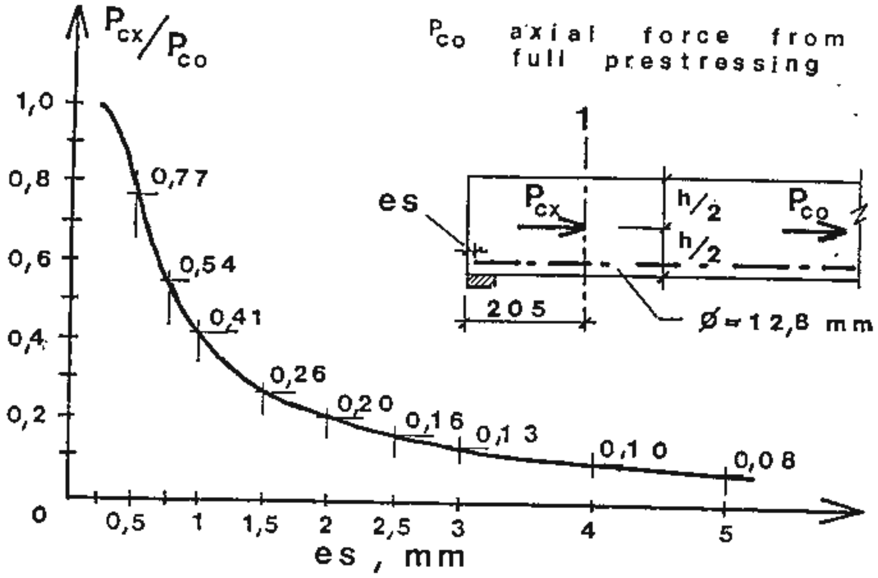


Fig. 11. Relationship between the axial force P_{CX},from the prestressing, on the concrete and the free end slip es of the strand at the cross-section where the max. principal tensile stress occurs. Computed with FEM-analysis. The development of the prestressing force P_{SX} is based on curve B in Fig. 9.

The scatter of the strength of most of the drilled cores was large in contrast to the scatter of the shear capacity of the slabs and the strength of the cast cylinders and cubes. This is due to the small diameter of the cores which makes it difficult to get representative concrete and which makes it necessary to have very accurate surfaces in the specimens.

The shear capacity of some tested slabs and beams was also compared with the calculated capacity. The concrete tensile strength was derived on the basis of this comparison.

Finally the concrete tensile strength was chosen as the most probable value of all the results. The relationship between the tensile strength and the age of the concrete is shown in Fig. 14.

The concrete tensile strength at failure in N/mm² as shown in Fig. 14 is given by:

$$f_{ctu} = 4.5 + 0.21 \log j \qquad (15)$$

5. SHEAR CAPACITY OF THE HOLLOW-CORE SLABS AT FAILURE

The principal tensile failure which is found to be the decisive design shear capacity for Dycore and Spiroll is considered below.

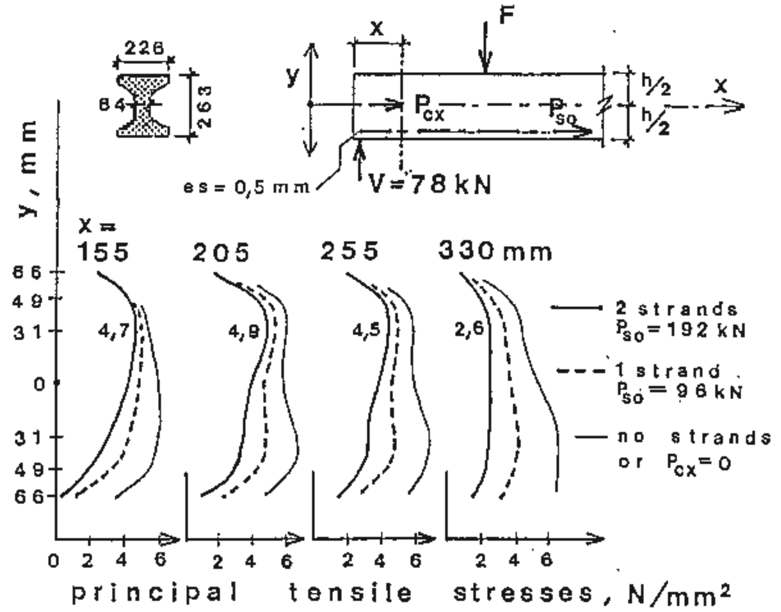


Fig. 12. Principal tensile stresses in different cross-sections of the inner web in Dycore. Vertical load and prestressing. Computed with FEM-analysis.The dimensions and the shear capacity correspond with the average value of 4 tested beams.

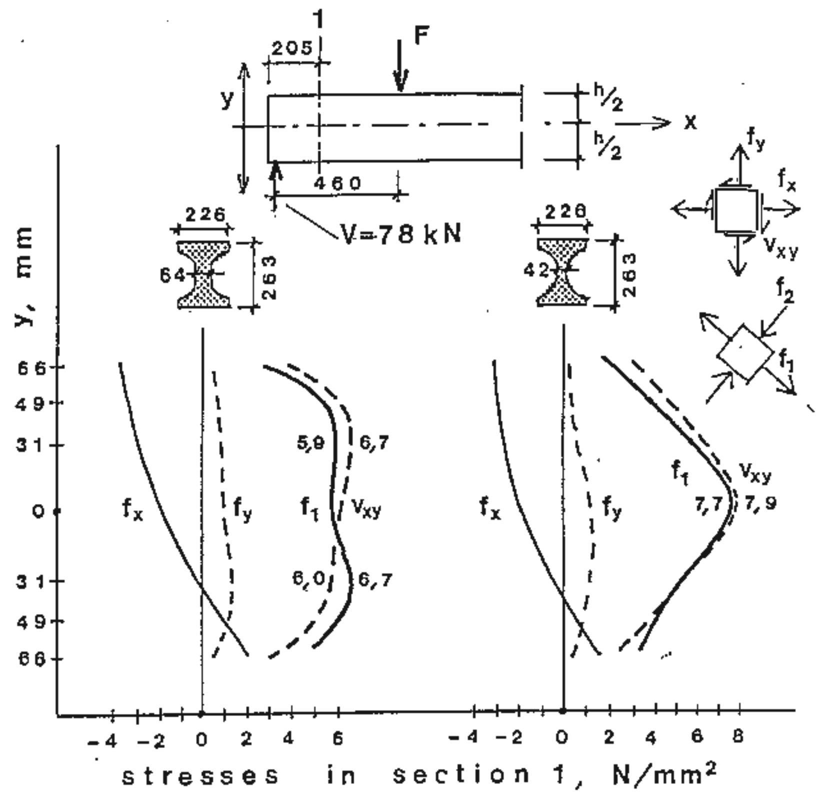


Fig. 13. Stresses in the inner web in Dycore in the cross-section where the principal tensile stress is max. Vertical load only. Computed with FEM-analysis. The dimensions and the shear capacity correspond with the average value of 4 tested beams.

In the actual range of prestressing in Dycore and Spiroll with height 265 mm the following equation is found to be more exact than Eq. (2):

$$v_{xy} = f_{ctu} + 0.4 f_{pw} \tag{16}$$

The compression f_{pw} from the prestressing is given by Eq. (13). The influence of the free end slip es of the strand on the shear strength of the web is shown in Fig. 15. This figure shows the large increasing of the shear strength v_{xy} when the free end slip es decreases from 1.0 to 0.5 mm. When es decreases from 2.0 to 1.0 mm or from 0.5 to 0.3 mm the increase of v_{xy} is small. When es decreases from 3.0 to 2.0 mm or from 0.3 mm the increase of v_{xy} is practically equal to zero.

According to the new calculation principle (Sec.4.2) the weakest inner web in Dycore and Spiroll governs the shear capacity.

Hence the shear capacity at failure of the slab is given by:

$$V_u = B/b_f{*}V_{wu} \tag{17}$$

The average shear capacity at failure in laboratory tests with uniformly distributed support pressure along the width of the slab is given by Eqs. (17), (14), (16) and (13), which give:

$$V_u = B/b_f{*}k(f_{ctu} + 1/\Phi{*}1.6/es{*}P_{so}/A_{cw})b_w\ h \tag{18}$$

The concrete strength f_{ctu} is given by Eq. (15).

6. COMPARISON OF TESTS AND CALCULATIONS

The ratio between the tested and the calculated shear capacity is shown in Fig. 16. The ratio is very close to 1.00 for most of the tests which seems to indicate that both the execution of the tests and the calculations are sufficiently accurate.

The axial force in the weakest inner web, from the prestressing, is based on the assumption that the strands in the neighbouring webs can not contribute to this force.

7. DESIGN SHEAR CAPACITY OF THE HOLLOW-CORE SLABS

The design shear capacity at failure in the building is based on Eq. (18) and given by:

$$V_d = K_R{*}B/b_f{*}k(K_B{*}f_{ctu}/K_c + K_p{*}1/\Phi{*}1.6/es{*}P_{so}/A_{cw})b_w\ h \tag{19}$$

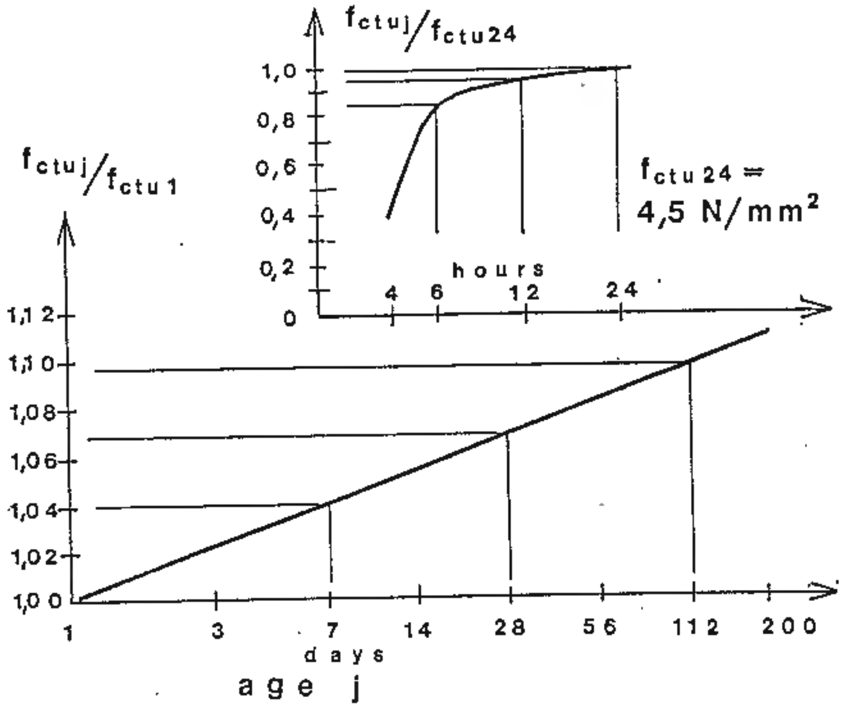


Fig. 14. Relationship between the concrete tensile strength f_{ctuj} and the age for extruded concrete in Dycore and Spiroll with height 265 mm. The benches in the factories were heated.

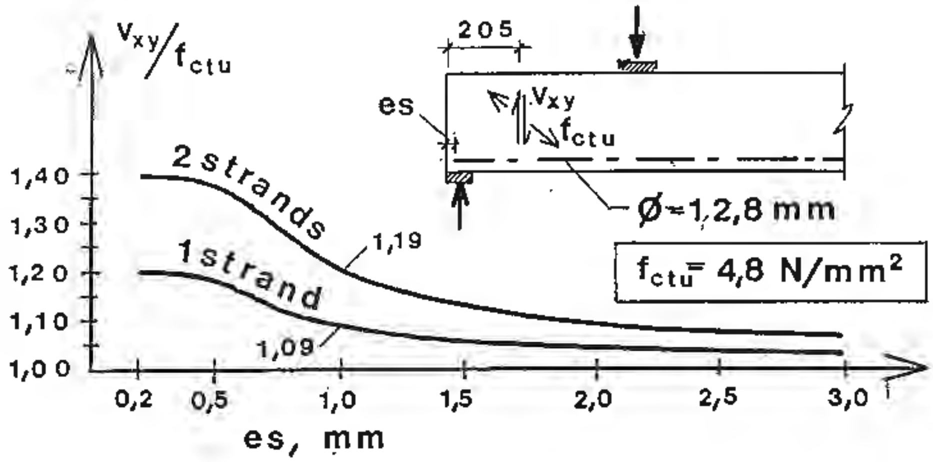


Fig. 15. Relationship between the shear strength v_{xy} and the free end slip es of the strand in the inner web in Dycore and Spiroll with height 265 mm. Calculation based on Eqs. (16) and (13), Fig. 11 and the age of concrete equal to 28 days.

It is the author's considered opinion that the safety coefficients at least should be:

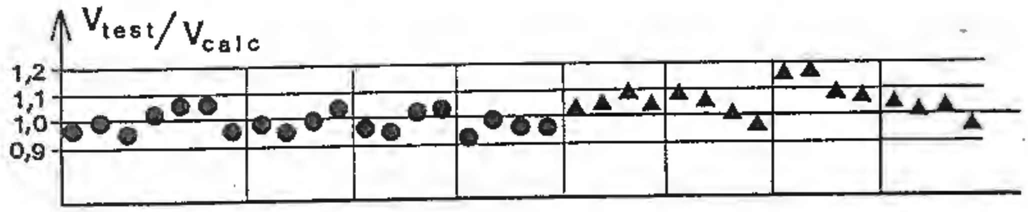
K_C: Safety coefficient for concrete, see below

K_P: Load factor for prestressing = 0.9

K_R: Reduction coefficient for the capacity = 0.75
(the support pressure may have accidental concentrations along the width of the slab)

K_B: Conversion factor = 0.85
(from the average capacity in the laboratory to the characteristic capacity in the building)

The hollow-core slabs behave as unreinforced near the support when the first crack occurs. According to Refs. /7/ and /10/ the basic coefficient K_c for tensile failure in the concrete is 3.5 when the concrete is unreinforced.



age	27-35	1	38-42	71-72	104-106	111-112	45-51	119-121	days
ø	12,8	12,8	12,8	12,8	12,8 9,5	12,8	12,8 9,5	12,8	mm
es	0,4-1,1	0,5-1,0	0,5-0,8	0,3-0,7	0,7-1,7	0,9-1,3	0,4-1,0	0,8-0,9	mm
a/d	2	2	2	3	2	2	2	2	
A_s	700		1000		400	700		1000	mm^2
	Dycore				Spiroll				

Fig. 16. Ratio between the tested and the calculated shear capacity at failure for slabs with nominal height 265 mm. The calculation is based on the measured dimensions.

K_c may be reduced to the following according to Ref. /7/:

A. 75 % if there is little probability that cracks will occur in the important region of the structure before max. load

B. 75 % if cracks in only one part of the structures do not cause collapse of the whole structure.

According to the principle which is given in Ref. /10/ Kc may be reduced to the following:

C. 1.4/1.25 = 89 % if the smallest web thickness and slab height are used, which occur in the building

When the reductions A and B are possible, K_c is equal to 1.97
When the reduction A, B and C are possible, K_c is equal to 1.75

If the free end slip of the strands is smaller than 1.0 mm, the compression from the prestressing in the shear region is considerable. In this case the concrete quality is usually high and a further reduction of K_c is probably possible. However, it is not possible to specify a reduction before this is investigated.

With the safety coefficients above and when the reduction A-C is possible for K_c, Eq. (19) becomes:

$$V_d = 0.75*B/b_f*k(0.5f_{ctu} + 1/\Phi*1.44/es*P_{so}/A_{cw})b_w\ h \qquad (20)$$

After 28 days the average concrete tensile strength at failure is 4.8 N/mm². The stress in the strands is normally f_{so} = 1200 N/mm² before releasing the strands in the factory. The nominal area of the inner web in Dycore and Spiroll A_{cw} = $34*10^3$ mm², when the nominal height is 265 mm. The further nominal values are:

B=1200mm and b_f=225mm.With these values Eq.(20) becomes:

<u>For Dycore</u>:

$$V_d = 2.84(2.4 + 0.004*A_{sw}/es)b_w\ h \qquad (20a)$$

<u>For Spiroll</u>:

$$V_d = 3.64(2.4 + 0.004*A_{sw}/es)b_w\ h \qquad (20b)$$

An important question is connected to the area of strands which can be regarded as effective in the weakest or most stressed inner web.

It is the author's opinion that the effective area A_{sw} should be calculated for the design shear capacity as follows:

A. p=A_{sw}/es (mean value in each web) is larger in the two neighbouring webs than in the weakest web.
The effective value of p in the weakest web can be calculated as the average value of p in the weakest web and 75 % of p in the neighbouring webs, if this value is larger than p in the weakest web.

The calculation does not quite express the behaviour at failure. However, the calculation is reasonable because the larger axial forces in the neighbouring webs increase the safety against cracks before max. load.

B. If one or more webs are removed (blockouts) in the shear region, the concrete in these webs is poor or there is no sufficient support for these webs, they should be neglected in the shear calculation.

The most stressed web in the remaining slab governs the shear capacity. The load on this web has to be calculated. In this case the effect of the axial force in the neighbouring webs will be neglected.But,the value of the reduction coefficient K_R should in this case be 85 % instead of 75 %.

C. If there are load concentrations along the width of the slab in the shear region,the same principle may be used as in Sec. B.

8. CONCLUSIONS

The design capacity of these types of slabs at the region near the support is either bending or shear governed by principal tensile. Consequently it is not necessary to calculate the design shear bending capacity or the design anchorage capacity of these slabs.

When the load is concentrated near the support or distributed along the length of very short slabs, the bending capacity may be governed by the tensile strength of the concrete and the compression from the prestressing. This applies especially if the number of strands is small and/or the free end slip of the strands is large.

It is necessary to calculate with accidental concentrations along the width of the slab. The corresponding reduction of the design shear capacity is considerable. It is also necessary to include the fact that the characteristic capacity in the building may be smaller than the characteristic capacity based on only a few tests in the laboratory.

The design shear capacity is influenced by the area of the strands and by the free end slip of the strands.

Therefore, it is necessary to guarantee the maximum value of the slip based on control in the factory.

Even if the slip is large the shear capacity may be high enough. But the bending capacity at the region near the support may be too small. However, if both capacities are high enough the slip should not be larger than a certain value. This is due to the concrete quality which may be poor if the free end slip of the strand is very large. The probability that cracks will occur before max. load increases when the free end slip is large.

When the free end slip of one strand in the slab is larger than 5 mm, the slab should not be used.

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10. NOTATION

B = width of the slab, in mm
b_f = "width" of the flange of the inner web, in mm
V_{wu} = shear capacity of the weakest or most stressed inner web
k = 0.71 for Dycore and k = 0.91 for Spiroll
f_{ctu} = concrete strength given by Eq. (15), in N/mm²
j = days within the range 1-200
Φ = strand diameter, in mm in the range 9.5-12.8
es = free end slip of the strands, in mm in the range 0.5-5.0
P_{co} = axial force (from the prestressing) in the cross-section of the inner web at the time when the strands are released in the factory, in N
P_{so} = prestressing force before releasing in the factory, in N
P_{sx} = prestressing force under development from the free end
A_{cw} = area of the inner web with "flanges", in mm²
b_w = smallest thickness of the inner web, in mm
h = height of the inner web, in mm
f_p = compression from prestressing
f_{so} = stress in the strands before releasing in the factory
J = moment of inertia
S = statical moment
A_s = area of all strands in the slab
E_s = modulus of elasticity of strand
dx = infinitesimal length
l_t = transmission length

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