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Horizontal shear strength in rib and block slab systems

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A recent amendment to the horizontal shear clause of SABS 0100 requires that the average horizontal shear stress be distributed according to the shape of the shear diagram. This change effectively doubled the design shear stress in simply supported members subjected to a uniformly distributed load, and therefore threatened the economy of rib and block slabs. In response, a study into the specifications of international codes of practice was undertaken and compared with the South African code. An extensive experimental programme was also conducted to determine the shear capacity along the contact interface of the in-situ concrete and precast ribs. It was found that the South African specification (as amended) is consistent with other international codes. It was also found that the surface roughness has a profound influence on the horizontal shear capacity and is a better indicator of shear strength than the strength of the in-situ concrete.

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INTRODUCTION

In recent years, the horizontal shear in rib and block slab systems have been a concern to engineers and manufacturers alike, for several reasons: firstly, SABS 0100 (South African Bureau of Standards 1992) published a method to determine the horizontal shear, which was later refuted and changed in March 1998 to match the method subscribed in BS 8110 (British Standards 1997). The change effectively doubled the shear stress between the interface of the precast rib and in-situ concrete (ie, for a simply supported rib and block slab subjected to a uniformly distributed load). This led to a general uneasiness amongst manufacturers and engineers who may have based their designs on the original method. This further led to a lack of confidence in the code and questions have been raised whether the revised method or the original method is in fact correct. Secondly, the width of the contact interface is relatively small (between 60 and 200 mm). The shear stresses are concentrated in this region and are potentially the 'bottle neck' of the design. For this reason, the change made to the code has serious implications and threatens the economy of the rib and block slab system. In response, research was initiated to answer three fundamental questions:

- Is the method of calculating the horizontal shear, as prescribed by SABS 0100, consistent with international codes of practice?
- Are the permissible shear strengths listed in table 42 of SABS 0100 consistent with international codes of practice?
- Are locally produced ribs able to achieve the shear strengths listed in table 42? Furthermore, are the permissible shear strengths reasonable or overly conservative?

To answer the first question, a comparative study of four codes of practice was undertaken, namely ACI 318 (American Concrete Institute 1995), Eurocode 2 (CEN 1999), BS 8110 and SABS 0100. The second question was answered by comparing the allowable shear strengths (table 42 of SABS 0100) with the codes stated above. The third question was answered by experimentally determining the horizontal shear capacity between the interface of precast ribs and in-situ concrete. In total, 90 tests were done. The results are compared with the South African code.

A STUDY OF HORIZONTAL SHEAR AND INTERNATIONAL CODES

Horizontal shear and ACI 318-95

The ACI gives three methods as options for assessing the horizontal shear. The first method, given in section 17.5, is based on an assessment of the vertical shear, which is assumed to satisfy the horizontal shear requirements. A review of fundamental shear theory would demonstrate the relationship between vertical and horizontal shear and therefore give credence to this method. Furthermore (depending on the configuration of the member), vertical shear often precedes horizontal shear. Thus, by resisting the vertical shear, horizontal shear is catered for.

The second method is the shear friction method, which is described in section 11.7. An initial assumption is made that the interface is cracked along the shear plane. The relative displacement along the crack line is resisted by friction. This friction can only be developed if reinforcement is placed perpendicular to the shear plane for the purpose of developing a perpendicular force. In the majority of the rib and block slabs investigated, the amount of shear steel across the interface is far less than the minimum steel requirement. For this reason, the shear friction method is not generally applicable to rib and block slabs as constructed in South Africa.

The ACI also allows an alternative method that is similar to the method endorsed by BS 8110 and SABS 0100. As stated by the ACI:

> As an alternative to 17.5.2, horizontal shear shall be determined by computing the actual change in compressive or tensile force in any segment, and provisions shall be made to transfer that force as horizontal shear to the supporting element. The factored shear force shall not exceed horizontal shear strength V_{nh} as given in Sections 17.5.2.1 through 17.5.2.4, where area of contact surface A_c shall be substituted for $b_v d$.

Various authors (MacGregor 1988; Nilson 1987; Wang & Salomon 1973) have written and provided examples demonstrating how to apply this method. However, owing to a lack of clarity in prior versions of the code, many authors have assumed that the shear transferred is an average force over the length of the contact area. No attempt was made to distribute this force in accordance with the shape of the shear diagram. It appears that many designers have assumed that the shear forces will redistribute similarly to the assumptions made with composite steel/concrete beams. Since earlier versions of the code did not give any guidance in this regard, design procedures followed composite steel/concrete design techniques. The slip between a composite concrete slab and a steel beam is relatively large due to the difference in stiffness of each material. This causes a redistribution of force and therefore an average stress can be assumed. In composite construction, where both materials are concrete, the prevailing opinion is that the slip is small and therefore the redistribution of stress is limited and confined to a small region. For this reason, the commentary to the 1995 version of the ACI code indicates that the average stress must be distributed according to the shape of the shear diagram.

Horizontal shear, BS 8110-1:1997 and SABS 0100-1992

The methods to determine the horizontal shear in BS 8110 and SABS 0100 are similar in many respects to the specifications of the ACI. As stated in section 5.4.7 of BS 8110:

> 5.4.7.1 Horizontal shear force due to design ultimate loads. At the interface of the precast and in-situ components the horizontal shear force due to design ultimate loads is either:
>
> (a) where the interface is in the tension zone: the total compression (or tension) calculated from the ultimate bending moment; or
> (b) where the interface is in the compression zone: the compression from that part of the compression zone above the interface, calculated from the ultimate bending moment.
>
> 5.4.7.2 Average horizontal design shear stress. The average horizontal design shear is calculated by dividing the design horizontal shear force by the area obtained by multiplying the contact width by the beam length between the point of maximum positive or negative design moment and the point of zero moment.
>
> The average design shear stress should then be distributed in proportion to the vertical design shear force diagram to give the horizontal shear at any point along the length of the member. The design shear stress, v_h, should be less than the appropriate value in table 5.5.

Although the wording differs slightly between BS 8110 and SABS 0100, the specifications are fundamentally identical. Prior to March 1998, the only significant difference is the question of how the horizontal shear should be distributed and what stress should be compared with table 42 of SABS 0100 (average or maximum?). As amended, SABS 0100 is now agreeable with other codes.

The BS 8110 and SABS 0100 methods are similar in many respects to the alternative method given in ACI 318. There are some differences in permissible shear strengths (see table 1), but the method for calculating the horizontal shear is identical – at least interpreted as identical. The ACI code gives a generalised statement whereas the British and South African codes are far more specific in how the calculation should be performed.

Consistent with SABS 0100 and BS 8110, an equation to determine the design average horizontal shear is given below assuming the interface and precast rib are located in the tension zone:

$$v_h = \frac{2 f_y A_s}{\gamma_m b_i l} \qquad (1)$$

where fy is the yield strength of the steel, As is the area of steel in the precast rib, bi is the width of the contact interface, l is the span length and γ_m is the material factor.

Horizontal shear and Eurocode 2

Eurocode 2 is still in draft form, but is scheduled to be released in 2001. In the code, a section is included on the horizontal shear between precast and in-situ concrete (section 6.2.6). The equations to determine the horizontal shear are based on elastic formulations:

$$v_{Edi} = \frac{V_{Edi} S}{b_i I} < \frac{V_{Edi}}{b_i d} \qquad (2)$$

where V_{Edi} is the vertical shear force, S is the moment of area, b_i is the width of the interface, I is the moment of inertia and d is the effective depth of the reinforcement.

The expression on the right of the less than symbol is the average vertical shear stress and the other expression is the maximum shear stress (horizontal and vertical) at the contact interface. Although many early codes used elastic equations to determine the shear stress, the majority have replaced these equations with those which reflect ultimate limit state conditions. In addition, there is a lack of consonance between this section and section 6.2.5 of the same code, which determines the shear between the web and flanges of T-sections. In this section, the horizontal shear is determined similarly to BS 8110, SABS 0100 and the alternative method of ACI 318.

Since the code is still in draft form, care should be taken in applying this section, which contains numerous typographical errors.

A comparison of horizontal shear strengths

Table 1 is a comparison of horizontal shear strengths from ACI 318, BS 8110, SABS 0100 and Eurocode 2. By inspection, table 1 indicates a good correlation between the codes except when shear steel is provided. If minimum steel is provided, BS 8110 and SABS 0100 allow a much higher shear strength. The surfaces that are most applicable to rib and block slabs in South Africa are those which are intentionally roughened but nominal shear steel is not provided. For this case, ACI 318, BS 8110 and SABS 0100 agree on an identical value of 0,6 MPa for an in-situ concrete strength of 25 MPa.

The Eurocode appears conservative in contrast to the other codes. A range of shear strengths is given which reflects the influence of the surface roughness and the frictional resistance due to externally applied loads. In determining these values, domestic and light industrial loads were assumed.

HORIZONTAL SHEAR EXPERIMENTS

Description of test specimens, concrete mix and test rig

A composite member is designed to act monolithically. However, the precast rib and the in-situ concrete tend to slide relative to each other, as illustrated in figure 1 (page 26). The inducted horizontal shears, due to bending action, are resisted by the shear capacity of the interface. It is common to model this shear behaviour by the 'push-off' test method (Lam *et al* 1998; Choi *et al* 1999). The test rig is illustrated in figure 2; the rib is braced and the in-situ concrete is pushed by a ramping load until shearing occurs. The eccentricity of the applied load was set at 100 mm and the instability of the rig was rectified by placing a roller support at the top of the test samples.

Table 1 Comparison of horizontal shear strengths for an in-situ concrete strength of 25 MPa

Surface conditions	ACI 318-95 (MPa)	BS 8110-1:1997 & SABS 0100-1:1992 (MPa)	Eurocode 2 (draft) (MPa)
Clean, free of laitance and intentionally roughened	0,6	0,6 (Roughened only)	0,45 to 0,5 (Roughened and frictional resistance due to externally applied loads)
Clean, free of laitance and minimum shear steel provided	0,6	2,1	Not available
Clean, free of laitance, intentionally roughened and minimum shear steel provided	1,8 to 3,5 (Depending on the quantity of shear steel)	1,8 (Roughened and minimum steel provided, but not of cleaned and free of laitance)	Not available

Table 2 Average surface roughness

Group(s)	No of specimens	Average amplitude of roughness (mm)
Ia	12	0,94
Ib	6	0,94
Ic	12	4,02
IIa	12	3,82
IIIa	12	3,09
IIIb	6	3,46
IIIc	6	4,22
IVa	12	3,41
Va	12	0,89

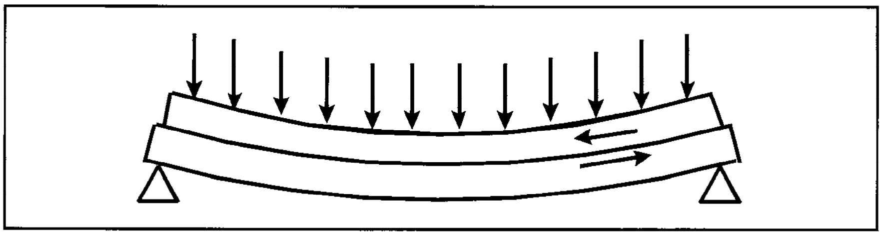

Figure 1 Horizontal shear along the interface of a composite member in flexure

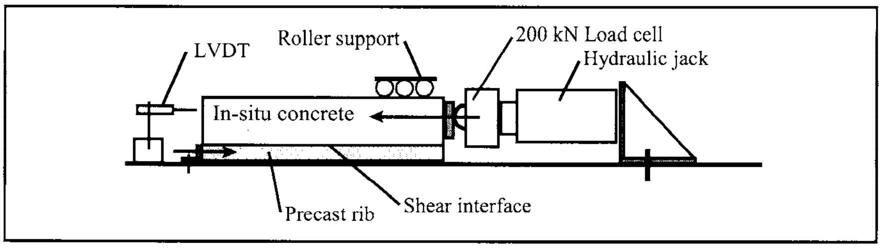

Figure 2 Push-off method for modelling horizontal shear

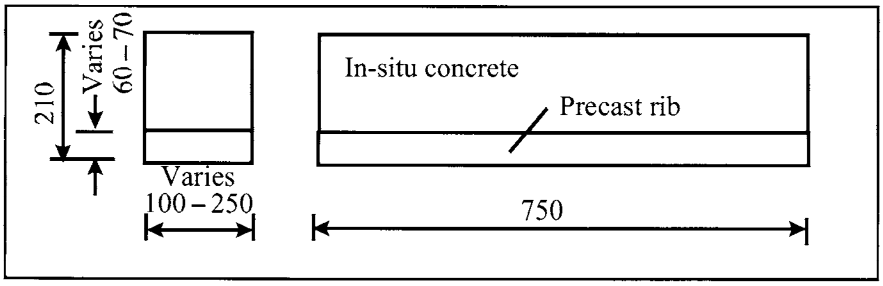

Figure 3 Basic dimensions of the test specimens

Table 3 Shear steel quantities across the interface of the test specimenss

Group(s)	Average steel per specimen (%)
Ia, Ic	0,06
Ib	No shear loops
IIa	0,07
IIIa, IIIb, IIIc	0,02
IVa	0,02
Va	0,10

The experimental programme included ribs from five manufacturers located throughout the country. Ribs were taken from various factories to get a diverse representation of the rib and block systems used throughout South Africa. The number of test specimens and the diversity of the tests tend to give credence to the results and are representative of South African conditions. Although all of the rib and block slab systems are basically the same, the size of the ribs, steel quantity and surface roughness varied. For each type of rib, six specimens were tested for in-situ concrete strengths of 25 and 30 MPa. In addition, several other tests were done to determine the influence of the so-called shear loops and surface roughness. In total, 90 specimens were tested.

The test specimens are of a composite construction – a precast rib with a block of in-situ concrete cast on top. The basic dimensions of the specimens are given in figure 3.

All of the specimens were cut to 750 mm in length. The depth of the precast rib varied from 60 to 70 mm, but the overall depth of the specimen was kept constant at 210 mm. The width of each specimen varied according to the original width of the rib (100 to 250 mm).

The mix design of the in-situ concrete is given below. The masses are dry weights in kg per cubic metre of concrete.

The mix is for a concrete strength of 40 MPa at 28 days; however, the specimens were tested at an earlier date when the concrete reached the test strength of 25 or 30 MPa.

Cement OPC 42.5	375 kg
Filler sand	125 kg
Crusher sand	765 kg
Stone 19	900 kg
Admixture	1 310 mℓ
Water	208 ℓ

In the majority of the specimens, the interface surface was intentionally roughened. The average roughness (based on an average of 15 to 30 readings) is given in table 2. The measured amplitudes are based on a wavelength of 20 mm.
Shear steel, in the form of loops, was provided at the interface of most of the specimens. Table 3 is a list of the quantities of shear steel across the contact interface of each test group.

Test results

A regression curve was fitted to the test data. The curve was then dropped to the 95% one-sided confidence interval. Procedures specified by BS 2846 (1975) were used in this regard (ie, statistical interpretation of data). The curve was further dropped by a material factor of 1,5, which is in accordance with table 42 of SABS 0100 and table 5.5 of BS 8110.

Table 4 Comparison of in-situ concrete strength/shear capacity with SABS 0100

	f_{cu} = 20 MPa	f_{cu} = 25 MPa	f_{cu} = 30 MPa	f_{cu} = 40 MPa
90 test specimens	0,31	0,41	0,51	0,70
SABS 0100 Roughened	–	0,60	0,65	0,75

Table 5 Horizontal shear strength compared with surface roughness (concrete strength not less than 25 MPa)

	Roughness amplitude 0 mm	Roughness amplitude 1 mm	Roughness amplitude 2 mm	Roughness amplitude 3 mm	Roughness amplitude 4 mm	Roughness amplitude 5 mm
90 test specimens	0,24	0,37	0,51	0,65	0,79	0,93

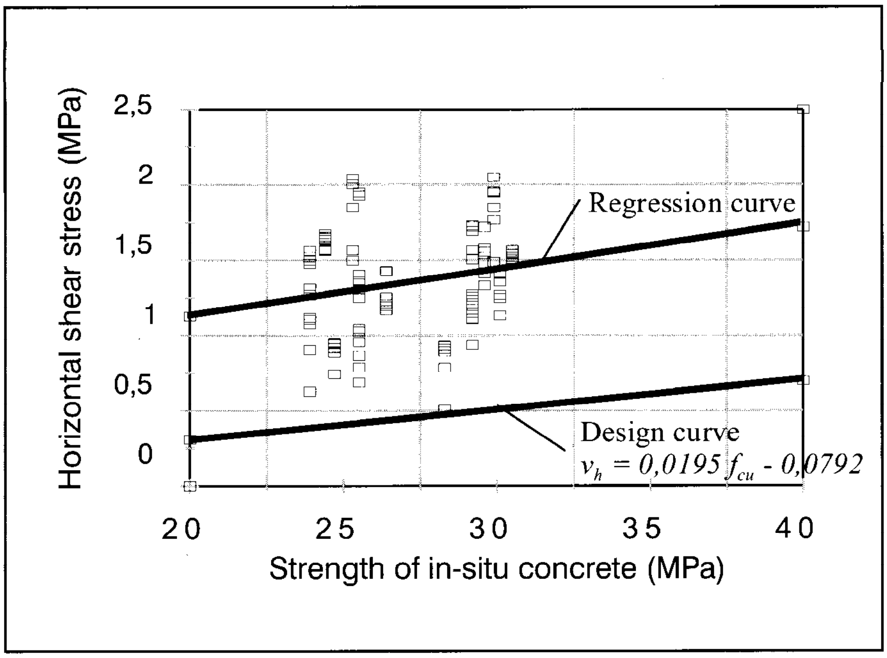

Figure 4 Horizontal shear strength versus the in-situ concrete strength

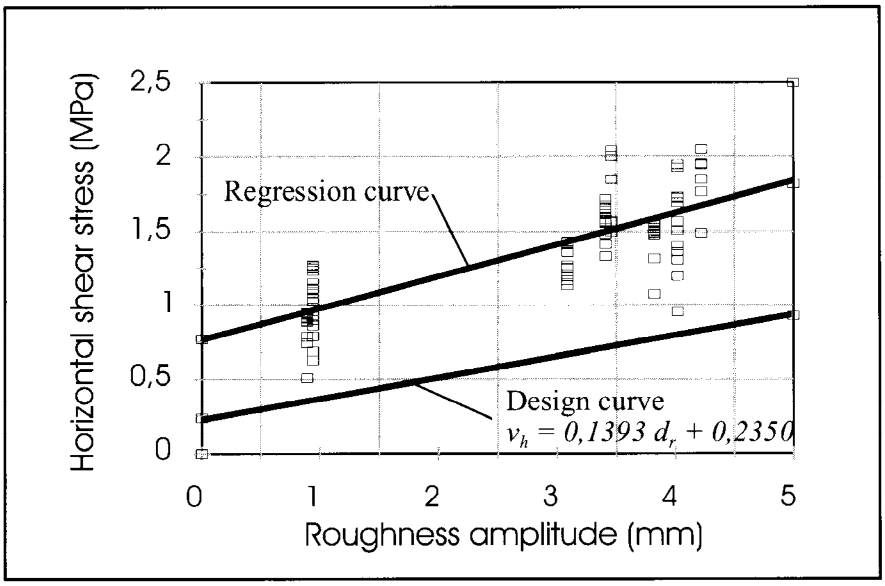

Figure 5 Horizontal shear versus roughness amplitude

Table 6 A comparison of test groups to determine the influence of shear loops

Test group	Average shear strength* (MPa)	Per cent steel	Roughness amplitude (mm)
Ia	0,95	0,06	0,94
Ib	1,02	No loops	0,94

*These values are not reduced to the 95% confidence interval nor modified by the material factor.

In table 4 and figure 4, the design horizontal shear stress is expressed as a function of the in-situ concrete strength. This is the traditional way of expressing design information on horizontal shear. Table 42 values (SABS 0100) are also given for a comparison with the code. By inspection, the design values determined from the experiments fall significantly below the values recommended by the code. In addition, the spread of the test data (see figure 4) is large, which indicates the influence of other parameters not expressed in the graph. Despite this there is an upward trend and a correlation with the in-situ concrete strength as indicated by the regression curve.

In table 5 and figure 5 the horizontal shear is expressed in terms of the interface roughness. The symbol d_r is the roughness amplitude over a wavelength of 20 mm. As illustrated in figure 5, the scatter is fairly tight, which indicates a good correlation between the roughness amplitude and the shear strength. In fact, it is evident by the experiments that there is a better correlation between the surface roughness and shear strength than with the in-situ concrete strength.

INTERPRETATION OF RESULTS AND RECOMMENDATIONS

The first objective was to determine if the method prescribed by SABS 0100 is consistent with international norms. The investigation led to the conclusion that it is consistent, but only if the corrections published in March 1998 are applied. More specific, the average shear stress should be distributed according to the shape of the shear diagram and the maximum shear should be compared with table 42 of SABS 0100. It could be debated that horizontal shear failure will not be confined (contrary to the ACI code) along contact surfaces which are not reinforced, but this work is left for future research.

The second question was whether or not the shear strengths listed in SABS 0100 are consistent with international codes. Although the codes investigated reflect similar values, they diverge considerably for surfaces which have minimum shear steel. However, the majority of rib and block slabs transfer the shear entirely by surface roughening; in this regard, the codes agree (with the exception of Eurocode 2) on an identical value of 0,6 MPa for 25 MPa concrete.

The answer to the question whether or not the shear capacities listed in table 42 of SABS 0100 are reasonable is both yes and no. The South African code is consistent with international norms, but some of the rib and block systems tested were not able to achieve the design strengths listed in table 42 of SABS 0100. It should not be misconstrued that the suppliers of these ribs are negligent or not meeting code requirements. The fault lies with the code, because it does not specify a minimum roughness amplitude. The code merely states the surface should be brushed, screeded or rough-tamped – no roughness amplitude is specified. In cases where the roughness amplitude of the brushed surface did not exceed 1 mm, the results were poor and below code values. In those cases where the surface roughness exceeded 3 mm, the results were significantly better. It is apparent from these tests that the surface roughness has a profound influence on the horizontal shear strength and should be a measure of the shear capacity rather than the in-situ concrete strength. However, the concrete strength does influence the shear capacity and a minimum strength should be specified. Table 5 and figure 5 are based on a minimum concrete strength of 25 MPa.

Test groups Ia and Ib are identical, with the exception of the shear loops – test group Ib loops were removed. A comparison of the results (see table 6) indicates that the quantity of steel across the shear plane is far too small to have any influence on the shear capacity. Several of the slab systems investigated fall into this category. It is apparent that unless minimum steel is provided, the influence of the steel on the shear strength should not be accounted for.

The design curves of figures 4 and 5 are based on in-situ concrete strengths between 25 and 30 MPa and a surface roughness up to 4 mm. Care should be taken when extrapolating beyond this range.

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