Determination of concrete compressive strength with pullout tests

H. Thun, U. Ohlsson and L. Elfgren

A pullout test using post-installed inserts has been examined as an alternative to drilled cores to determine the in-place concrete compressive strength. Tests have been carried out on eight railway bridges from 1965 to 1980 and on a one year old concrete slab. An empirical strength relationship is proposed between the compressive strength of a drilled core with the diameter and height of 100 mm and the pullout force from the pullout test. It is a power function and the relationship is valid for concrete compressive strengths up to 105 MPa; it gives higher concrete strengths than earlier proposed functions.

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Introduction

During the last few decades, it has become more and more important to assess, maintain and strengthen structures such as bridges, dams and buildings owing to a combination of increased loads, time-dependent deterioration, the increasing age of many structures and the high costs of building new infrastructure. Therefore, it is of great interest to find methods to evaluate existing concrete structures in an efficient way. A pullout test using post-installed inserts is examined for its ability to determine the in-place concrete compressive strength in old bridges. The method has primarily been intended for estimating the strength of the cover layer of new structures, see Germann Petersen and Poulsen[1] or Carino.[2]

The project was initiated in 1995 when an increase of the axle load was planned for a railway line and its bridges in northern Sweden, see Paulsson *et al.*[3,4] The object of the axle load increase, from 25 to 30 tons, was to reduce transportation costs for carrying iron ore from the mine fields in the mountains to the harbours in Luleå on the Gulf of Bothnia and in Narvik on the Norwegian Sea. The railway line is 473 km long and was built between 1884 and 1902. There are 112 bridges on the line, most of them rebuilt between 1950 and 1980. In order to check the present concrete strength in the bridges a study was carried out by Thun *et al.*[5,6]

Methods

Two methods have been used in this investigation to determine the in-place concrete compressive strength: drilled cores and pullout tests. These are described below.

Drilled cores. To drill out and test cores is a common method to estimate the in-place strength of the concrete in a structure. Many countries have adopted standard procedures for how a core should be prepared, stored and so on before testing. In the present study, the preparation, storage and so on have been carried out according to the Swedish concrete recommendations, BBK94.[7] A water-cooled drill with diamond edges has been used. The cores have then been air-cured for at least three days before testing, see Möller *et al.*[8] or EN 13971.[9] The reason for this is that the cores are moistened by water during the drilling and cutting process and this inflicts a reduction of the strength (about 10–15%) that needs to be considered, see Möller *et al.*[8] The ratio between the length and the diameter has been 1·0 and the diameter approximately 100 mm. The cores have been marked with a drill hole number and a serial number. The cores have been used for uniaxial tensile tests, splitting tensile tests and compressive tests. There is an established relationship between the compressive strength of a horizontally drilled core with the height and diameter of 100 mm and the compressive strength of a 150 mm cube, see Möller *et al.*[8] or EN 13971.[9] (According to Section 7.1 in EN 13971[9] 'Testing a core with equal length and nominal diameter of 100 mm gives a strength value equivalent to the strength value of a 150 mm cube manufactured and cured under the same conditions.') The present authors' tests confirm that there is no statistically significant difference between the means of the two samples (95% confidence level), that is, between the mean compressive cube strength 97·4 MPa (mean value of six cubes) and the mean compressive core strength 98·4 MPa (mean value of 24 cores with a standard deviation of 3·6 MPa). Thus, the compressive strength determined from drilled cores has in this study been regarded to represent the 'true compressive strength', as it constitutes the reference method in the new standard for assessment of in-situ compressive strength in structures and precast concrete components (see e.g. EN 13971).[9]

Pullout tests. The failure mechanism when an anchor bolt is pulled out has been investigated extensively both by way of experimental and analytical studies and an overview can be found, for example, in Eligehausen *et al.*[10] Results from fracture mechanics analyses and a round-robin study of plane stress and axisymmetric tests are presented by Elfgren *et al.*,[11-14] see Figure 1. An example of a specific study can also be found in Ohlsson and Olofsson.[15] In these studies it is shown

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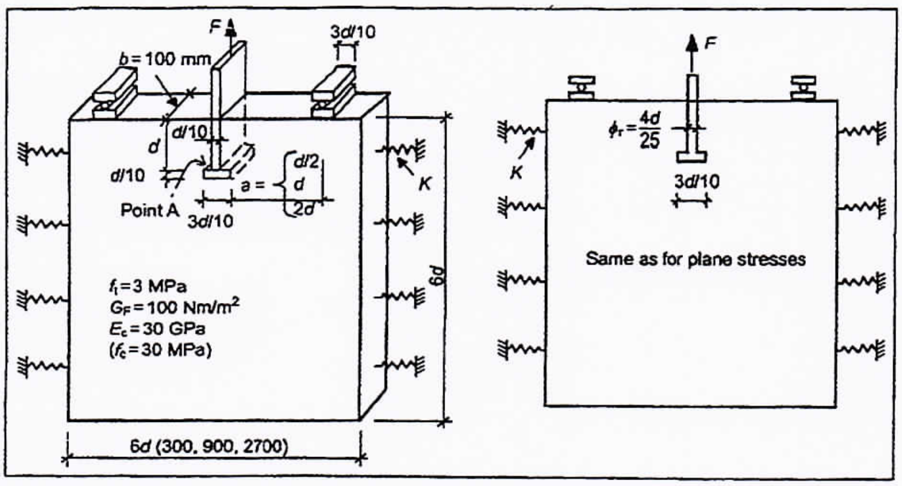

Figure 1 Round robin analyses and tests of anchor bolts for plane stresses (left) and axisymmetric stresses (right) for varying embedment depths d = 50 mm, 150 mm and 450 mm (Elfgren *et al.*[11,12])

that the geometry, the boundary conditions and the material properties are very important to the outcome of the results. For the pullout test method, overviews are presented by Carino[2] and Bungey and Millard,[16] and specific studies are presented, for example, by Yener,[17] Ottoson,[18] or Stone and Carino.[19,20] The pullout test subjects the concrete to a non-uniform three-dimensional state of stress. A primary stable crack system is initiated from the insert at an early stage and propagates into the concrete at a large apex angle (the angle depends on the system geometry and common angles are between 30° and 70°), see Figure 2. Then, governed by the distance to the supports, which gives a counter pressure to the pullout force, a second system arises. This second system develops to form the shape of the extracted cone, see Figure 2. In the literature, different hypotheses for the failure mechanism at the ultimate load have been suggested. Some researchers argue that compression failure is the main reason for failure, some say aggregate interlocking is responsible, whereas others cite shear/tensile failure of concrete, for examples see the surveys by Carino[2] or Yener.[17]

The specific post-installed pullout test used in this investigation is called the Capo-test (see Germann Petersen and Poulsen[1]). The test procedure consists of drilling a 65 mm deep hole with a diameter of 18 mm using a water-cooled diamond bit, see Figure 2. Then a 25 mm recess is made at a depth of 25 mm using a portable router. An expandable split steel ring is inserted through the hole in the recess and expanded by means of a special tool. Finally the ring is pulled through a 55 mm reaction ring, pressure placed concentrically on the surface. A description of the method can also be found in Bungey and Millard.[16] The pullout force, F, is measured by the pull apparatus and can be converted into concrete compressive strength, f'_c, by means of calibration charts provided by Germann Petersen and Poulsen.[1] In Figure 3 the suggested general correlation for standard 150 mm (5·9 in) cubes is presented and the equations are

$$F = 0{\cdot}71\, f'_c + 2 \leq 50\text{kN} \tag{1}$$

$$F = 0{\cdot}63\, f'_c + 6 \geq 50\text{kN} \tag{2}$$

The background to the correlation charts is several laboratory and field studies made by the manufacturer as well as by other researchers.

When the two different types of test methods were compared in this project, it was concluded that the pullout test was a simpler and less expensive test to perform compared with drilling out cores on the bridges. The pullout test had the advantage that the equipment was lighter and easier to transport to the bridge compared with the equipment used for drilling out cores. This was one of the key advantages, as many of the bridges in this investigation could only be reached by train or on foot. Important in this case was also the fact that the pullout test inflicted less damage on the bridges.

Rockström and Molin[21] have shown that the relation suggested by Germann Petersen,[22] Equations 1 and 2, can be improved when the test object is an old structure, such as an old road bridge. They obtained higher concrete strengths according to Equation 3 in Figure 3, when they performed tests with both the pullout test and drilled cores on six road bridges that were aged up to 54 years. The equation proposed by Rockström and Molin is

$$F = 0{\cdot}55\, f'_c + 3{\cdot}16(\text{kN}) \tag{3}$$

The reasons for this discrepancy for old structures could, according to Rockström and Molin, be

(a) difference in concrete strength of the

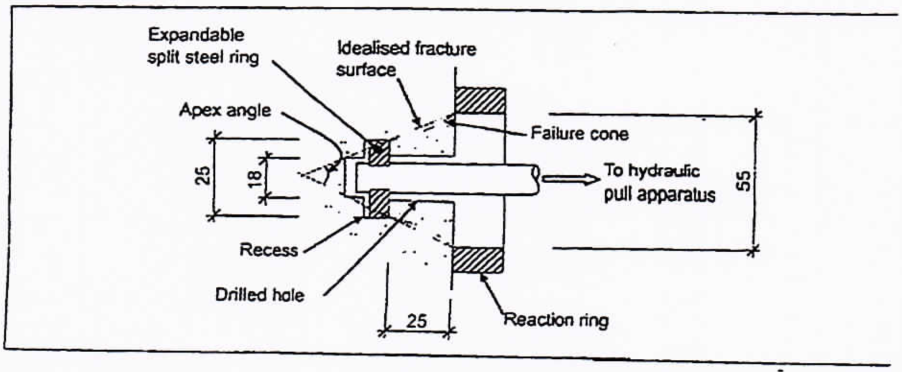

Figure 2 Schematic drawing of the pullout test, based on Germann Petersen and Poulsen,[1] Bungey and Millard,[16] and Carino[2] (dimensions in mm)

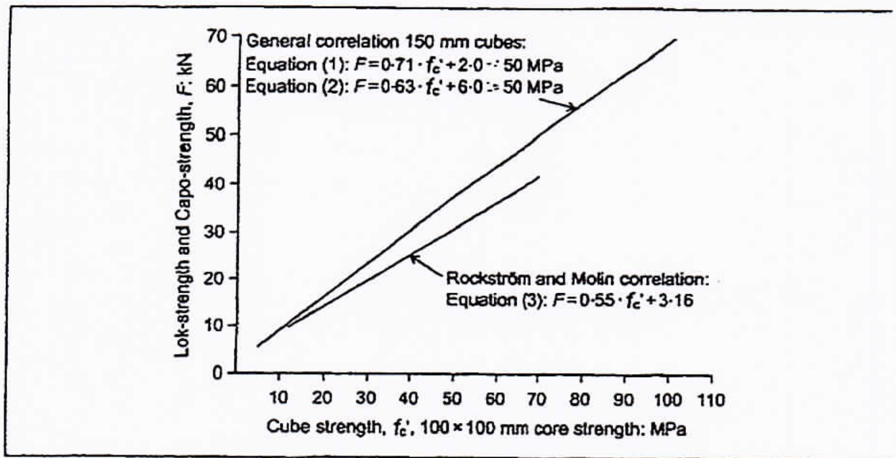

Figure 3 Correlation between pullout test (Capo test) and drilled cores with the height and the diameter of 100 mm, trimmed and air-cured for three days before testing, made by Rockström and Molin[21] based on five old Swedish bridges (results from one bridge had been rejected). The correlation is compared with the general correlation for 150 mm standard cubes suggested by the manufacturer (from Germann Petersen[22])

cover layer and concrete further into the structure

(*b*) for older structures the aggregate size may vary greatly

(*c*) risk of irregular and insufficient concrete compaction.

These three reasons are probably valid also for newly cast concrete – at least reasons (a) and (b). Also worth mentioning is that the study by Rockström and Molin was based on five objects, where the pullout test and cores were taken from the same test spot. Rockström and Molin rejected the results from one bridge because of the great difference between the pullout test and the drilled cores owing to low strength of the cover layer (high porosity). The result by Rockström and Molin was commented upon by Germann Petersen,[22] who suggested that the difference between the pullout test measured at the 25 mm surface layer and the core strength 75–100 mm deep found by Rockström and Molin may be explained partly by the three-day air-curing of the cores before testing, and partly by actual different concrete qualities at the two depth levels.

A point common for all studies of the pullout test is that a fairly good correlation has been found to exist between the pullout force and the concrete compressive strength. In this paper this correlation between the pullout force and the concrete compressive strength has been accepted and utilised to determine the in-place concrete compressive strength.

Investigation of concrete strength

Two series of tests have been performed. The first series is a field study of eight concrete trough bridges. Here the pullout tests are compared with drilled core tests. In the second series, a laboratory study is conducted.

Field survey of eight railway bridges

In order to obtain reference material regarding the relationship between the concrete compressive strength of drilled cores and the pullout forces from the pullout test, the concrete compressive strength was examined for eight railway bridges (road underpasses) during the late 1990s. The bridges were built between 1965 and 1980 with the Swedish concrete class K400 (in most cases), with a mean concrete compressive strength of approximately 45–47 MPa tested on 150 mm cubes after 28 days (maximum aggregate size of 32 mm).

In Table 1 a summary is presented of the results from the tests. Equations 1 and 2, and Figure 3, are used to calculate the compressive strength obtained with the pullout test. The mean concrete core compressive strength varies between 61·3 MPa and 85·3 MPa and the mean compressive strength calculated from the pullout force varies between 51·6 MPa and 76·9 MPa. These values are substantially lower than the ones from the concrete cores and indicate that the relationship between the pullout load, F, and the concrete compressive strength, f_c, ought to be improved for old concrete. In order to check this, a laboratory study was initiated.

Laboratory study

In order to check the difference obtained in the field study of the eight bridges, a simple laboratory test was performed. The aim of the test was to examine if the pullout test was 'surface sensitive'. First, a reinforced slab with the dimensions 0·35 × 0·70 × 1·4 m was cast and consolidated with a handheld stick vibrator in the laboratory, see Figure 4. The slab was then cut into two beams, dimensions 0·35 × 0·35 × 1·4 m, by using a water-cooled hydraulic saw with a diamond blade and performing the pullout test on both the cut surface and the mould surface. Between these two surfaces, cores were to be drilled so a comparison could be made between the pullout test and the drilled cores. The slab was cast on the ground in the laboratory as shown in Figure 4. The following concrete mixture was used (1 m^3): Cem I 42·5 BV/SR/LA: 432 kg/m^3, fine aggregate 0–8 mm: 910 kg/m^3, coarse aggregate 8–16 mm: 945 kg/m^3, silica fume: 39 kg/m^3, super-plasticiser: 1·1%, water reducing agent: 0·5%, water-to-cement ratio: 0·29, water-to-binder content: 0·27. The mixture was tested in connection with casting: the slump was 120 mm and the air content was 1·7%.

After the slab was cast it was stored for three days in the laboratory at room temperature. After these three days it was placed in a water tank with a water temperature of approximately +20°C. At 36 days after casting it was cut and the two 'beams' were again placed in the water tank, where they remained until the day the tests were performed, that is 398 days after casting. The pullout test was performed according to the

Table 1 Concrete compressive and tensile strengths for eight trough bridges determined with drilled cores and pullout tests. The cores are obtained from the longitudinal beams unless otherwise stipulated (drilled vertically from above in most cases). The pullout test compressive strength is evaluated with Equations 1 and 2, see Figure 2 (note: *m* is mean value, *s* is standard deviation and CoV is coefficient of variation)

Bridge no.*	Type of strength/force	Individual values								*m*	*s*	CoV
1	Pullout force, *F*: kN	–	–	–	–	34·9	45·6	46·5	33·4	40·1	5·4	0·13
	Compressive strength from pullout force†, f'_c: MPa	–	–	–	–	46·3	61·5	62·6	44,2	53·6	8·4	0·16
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	–	–	68·4	78·7	71·9	73·0	4·3	0·06
2	Pullout force from Capo-test, *F*: kN	–	–	–	–	48·8	46·7	50·3	54·3	50·0	2·5	0·05
	Compressive strength Capo-test†, f'_c: MPa	–	–	–	–	65·9	62·9	70·3	76·6	68·9	5·2	0·07
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	–	–	88·3	77·3	84·5	83·4	4·6	0·05
3	Pullout force from Capo-test, *F*: kN	–	–	–	–	42·7	41·2	41·7	46·4	43·0	2·0	0·05
	Compressive strength Capo-test†, f'_c: MPa	–	–	–	–	57·3	55·2	55·9	62·5	57·7	2·8	0·05
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	–	–	74·0	77·0	69·7	73·6	3·0	0·04
4	Pullout force from Capo-test, *F*: kN	48·7	45·0	36·6	33·8	42·1	31·2	32·3	39·5	38·7	5·9	0·15
	Compressive strength Capo-test†, f'_c: MPa	65·8	60·6	48·7	44·7	56·5	41·2	42·7	52·7	51·6	8·3	0·16
	Compressive strength drilled cores‡, f_{cc}: MPa	–	65·7	71·1	64·2	58·7	54·7	65·0	60·4	62·8	5·0	0·08
5	Pullout force from Capo-test, *F*: kN	–	–	–	–	49·1	52·4	52·9	38·5	48·3	5·2	0·11
	Compressive strength Capo-test†, f'_c: MPa	–	–	–	–	66·3	73·7	74·5	51·5	66·5	9·3	0·14
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	–	–	77·0	86·0	75·4	79·5	4·7	0·06
6	Pullout force from Capo-test, *F*: kN	–	–	–	–	–	58·3	46·5	45·1	50·0	5·1	0·10
	Compressive strength Capo-test†, f'_c: MPa	–	–	–	–	–	83·1	62·6	60·8	68·8	10·1	0·15
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	71·7	61·5	63·8	53·9	55·6	61·3	6·4	0·10
7	Pullout force from Capo-test, *F*: kN	–	–	–	–	42·6	49·2	35·6	45·5	43·2	4·5	0·10
	Compressive strength Capo-test†, f'_c: MPa	–	–	–	–	57·2	66·5	47·3	61·3	58·1	7·0	0·12
	Compressive strength drilled cores‡, f_{cc}: MPa	–	–	–	–	–	71·2	65·5	59·1	65·3	4·9	0·08
8	Slab: pullout force from Capo-test, *F*: kN	–	–	–	54·6	54·3	52·4	51·8	59·0	54·4	2·3	0·04
	Slab: compressive strength Capo-test†, f'_c: MPa	–	–	–	77·1	76·6	73·7	72·7	84·2	76·9	4·0	0·05
	Slab: compressive strength drilled cores‡, f_{cc}: MPa	–	–	80·3	83·4	86·4	83·9	88·3	89·2	85·3	3·4	0·04
	Beam: pullout force from Capo-test, *F*: kN	–	–	–	–	–	–	53·8	50·7	52·2	1·2	0·02
	Beam: compressive strength Capo-test†, f'_c: MPa	–	–	–	–	–	–	75·8	71·0	73·4	2·4	0·03
	Beam: compressive strength drilled cores‡, f_{cc}: MPa	69·9	70·8	78·2	66·5	69·3	74·1	74·0	77·8	72·6	4·2	0·06

* Bridge numbers: 1, Boden C (year of construction 1971); 2, Gamisonsgatan (1970); 3, Gammelstad (1970); 4, Luossajokk (1965); 5, Haparandavägen (1980); 6, Kallkällevägen (1966); 7, Bensbyvägen (1965); 8, Lautajokki (1967).

† Compression strength according to Equations 1 and 2.

‡ f_{cc} is the tested core compressive strength. Compressive strength for a drilled core with the height and diameter of 100 mm that has been tested in a test apparatus.

manufacturer's directions, which recommended corner/end distance of minimum 100 mm and 200–300 mm between each pullout test on the same horizontal level (the tests were performed during a period of about two weeks owing to problems with the equipment). A total of 12 pullout tests on each type of surface were performed and 12 cores, subsequently cut to provide 24 specimens, could be extracted (diameter of about 100 mm, height and diameter ratio of 1·0). In Figure 5 the results from the pullout test and the drilled cores are presented visually.

At the same time as the drilled cores were tested, six 150 mm standard cubes were also tested for compressive strength together with three 150 mm standard cubes that were exposed to a tensile splitting test (cast at the same time as the slab). These tests were performed according to the Swedish concrete standards (compare with EN 12390-6).[23] The mean concrete compressive strength was 97·4 MPa (the standard deviation was 2·7 MPa and the coefficient of variation was 0·03) for these six specimens and the mean splitting tensile strength was 5·7 MPa (the standard deviation was 0·3 MPa and the coefficient of variation was 0·05). The 28-day 150 mm standard cube compressive strength was 81·4 MPa (cube compressive strength, mean values of three cubes, after one day was 20 MPa, after 7 days it was 52·9 MPa and after 14 days the mean strength was 65·2 MPa).

Discussion and analysis

Field survey of eight railway bridges

In Table 1 it can be seen for bridge no. 8 that the compressive strength is higher in the slab (test 1) than in the longitudinal beams (test 2). The pullout test in fact gives a higher value of the concrete compressive strength for the slab than the drilled cores from the slab. One explanation could be that the slab contains micro-cracks in the tension zone (as the bridge has earlier been exposed to a fatigue test, see Paulsson *et al.*),[3,4] which are reflected in the cores partly taken from this zone, but not in the pullout test because this has been performed on the top surface – the

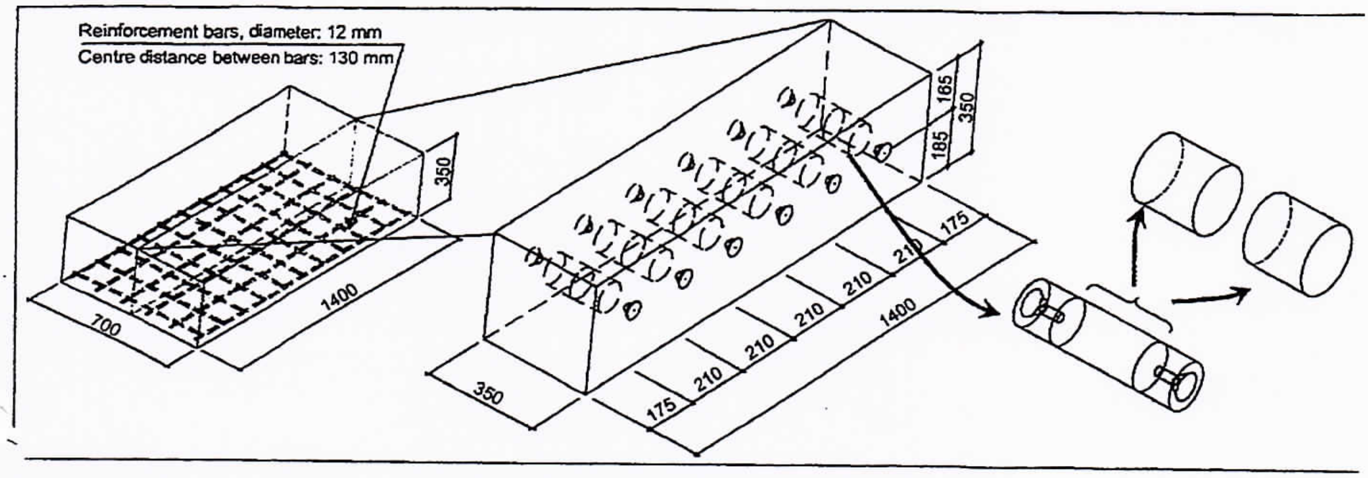

Figure 4 Dimensions of a slab cast in the laboratory (all measurements in mm)

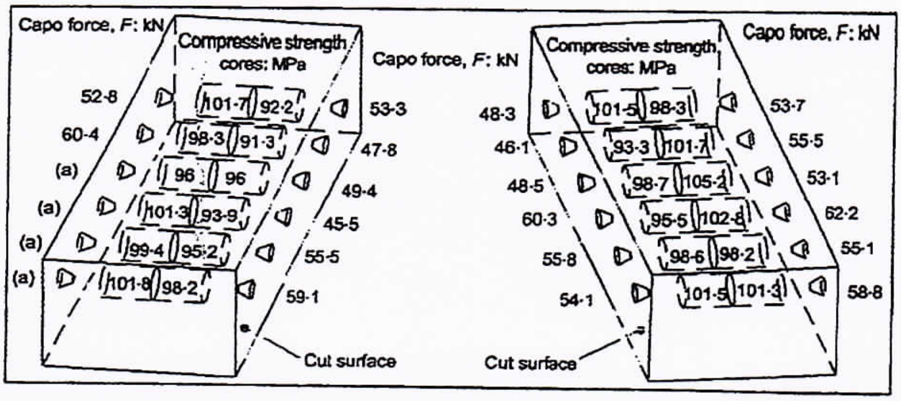

Figure 5 Diagram showing results from performed tests ((a) indicates the four ations where no result from the pullout test could be presented owing to uman error)

compression zone. Another explanation might be that too few pullout tests are performed on the slab and that they are also performed vertically. According to Germann Petersen and Poulsen,[1] testing the upper side of a slab gives a higher standard deviation than testing on a vertical surface.

In Table 1 it can be seen that for only two bridges (bridges nos 6 and 8) the core compressive strength becomes lower compared with the results from the pullout test. One reason for this could be that only three tests have been performed on these bridges, that is too few in comparison with the recommended four. For bridges nos 7 and 8 there is a difference between the pullout test d the core strength of about 8 MPa, but for the other bridges Equations 1 and 2 give very low concrete compressive strengths compared with the drilled core compressive strength. It is almost a difference of 20 MPa.

Laboratory study

When the values of the pullout force presented in Figure 5 are studied it can be seen that the pullout forces for the cut surface are lower than the pullout forces for the mould surface. The mean pullout force for the cut surface is 52 kN (the standard deviation is 5 kN and the coefficient of variation is 0·1). The mean pullout force for the mould surface is 56 kN (the standard deviation is 3·5 kN and the coefficient of variation is 0·06).

Statistical hypothesis test. One way to confirm or deny the difference statistically is to compare the mean values obtained on the two different surfaces. One approach to evaluate this is to perform a so-called statistical hypothesis test, which can be found, for example, in Montgomery[24] or Coladarci *et al.*[25] In this case a method called the two-sample *t*-test can be performed where the mean values of two groups are analysed if they are statistically different from each other. The following conditions have to be fulfilled: First, both samples are drawn from independent populations that can be described by a normal distribution; second, the observations are independent random variables; and third, the standard deviation or variances of both populations are equal. If it is assumed that the conditions above are fulfilled a test can be performed with the null hypothesis that the mean values for the different surfaces are equal. If the level of significance, α, is chosen to 0·05, an analysis leads to rejection of the null hypothesis at the 95% confidence level as the p value is less than 0·05, that is 0·044. Thus, the conclusion can be drawn that the pullout test gives different results for the two types of tested surfaces.

Why does the pullout test give higher values when performed on the mould surface? If the core strength is analysed, it can be seen in Figure 5 that the concrete core compressive strength varies even if the cores are lying next to each other and, as pointed out by Stone and Carino[19] or Germann

Petersen,[22] the pullout test measures only the concrete compressive strength of the cover layer and not the interior of the concrete structure. Furthermore, a lower concrete strength towards the centre of the slab is indicated if the core strength is analysed. The outer cores have a mean compressive strength of 100·5 MPa and a standard deviation of 2·5 MPa, compared with the inner cores that have a mean compressive strength of 96·3 MPa and a standard deviation of 3·4 MPa, and this difference is statistically significant at the 95% confidence level. There could be several reasons for this difference. One reason for the lower values on the cut surface could be that micro-cracks have formed when the surface was cut with the diamond blade, but this is something for future studies. Another explanation could be that there is a difference of moisture content between the two surfaces. As mentioned earlier a reduction of the strength for the cut surface occurs during the cutting process because the cut surface is moistened by water, see Möller *et al.*[8] However, as the two cut halves were placed in a water tank for more than a year before the test was performed, this difference in moisture content between the mould surface and the cut surface has most likely levelled out. Nevertheless, a difference in moisture content between the different pullout test spots arises during the actual testing period because it takes some time between the first and last test. Efforts have been made to reduce this by keeping the specimens wet and as sealed as possible until all the tests have been completed.

If the conclusion above is accepted, that the pullout test is sensitive to the surface, how does this influence the pullout force from an old concrete surface, such as an old concrete bridge? It has been seen that Equations 1 and 2 give lower strengths than the tested cores. If the reason for this difference is only because the pullout test is performed on an old surface, it seems realistic that a lower pullout force is obtained when the pullout test is performed on an old surface (even though the concrete compressive strength is high a bit further into the structure, for example, at the level where a core is obtained, which is often a few centimetres inwards). The surface of an old concrete bridge has often been exposed to environmental degradation over the years, for example carbonation (i.e. the reaction between the hydrated cement and carbon dioxide), which could reduce the concrete strength. Possibly more grinding of the surface is needed in the preparation phase of a pullout test when the pullout test is being performed on an old concrete surface.

Revised strength relationship for cores with diameter and height of about 100 mm

In order to establish a strength relationship between the pullout force from the pullout test and the compressive strength of a drilled core with a diameter and height of about 100 mm, the following have been carried out.

Field survey of eight bridges. The result from the tests on the eight railway bridges is used, that is the mean pullout forces are plotted against the mean compressive strengths from Table 1 – see the crosses in Figure 6. Unfortunately it is not possible to use all the data obtained in this study. Thus it is not possible to connect the pullout force from a pullout test to a certain core. This is owing to the fact that several companies have performed the tests and there is no record of core numbers (the cores were taken prior to this study). So it is only possible to connect the pullout force from the pullout tests to the concrete core compressive strength for a whole bridge. In Figure 6 two values for very old bridges are also presented, the ones denoted by a circle. As the cores from these bridges showed that the concrete used in the bridges was composed of a few very big aggregates (approximately 70 mm) and the rest were small (approximately 8 mm) combined with mortar, they are not included in the regression analysis. As can be seen in Figure 6, these two bridges give somewhat different values compared with the others. In Figure 6 it can be seen that this investigation has one so-called outliner (bridge no. 6 in Table 1, where $F = 50$ kN and $f_c' = 61{\cdot}3$ MPa). The reason for this could be that the mean pullout force for this bridge is based on only three values.

Laboratory study. If only the tests performed on the mould surface are used from the laboratory study (as this type of surface is similar to the type of surface that could be found on a bridge) and each pullout force is connected to the 'nearest' core compressive strength, for example 52·8 kN to 101·7 MPa in Figure 5, eight 'connected' values are obtained. If the 'connected' values are studied – the dots in Figure 6 – they show that lower pullout forces are obtained also for fairly newly cast concrete compared with the suggested general equation for 150 mm

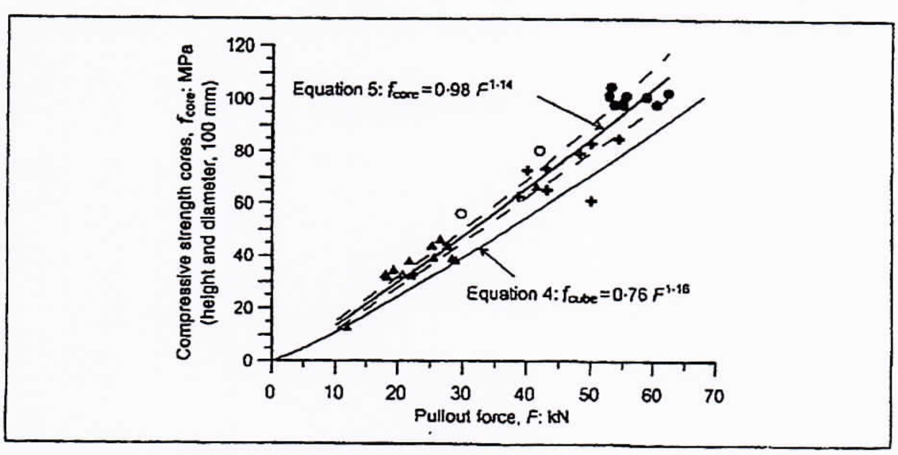

Figure 6 Proposed strength relationship, Equation 5, between the pullout force from the pullout test and drilled cores with the height and diameter ratio of 1·0 (diameter of about 100 mm). The dashed lines are confidence limits at the 95% confidence level. The equation is valid in the interval 11 MPa to 105 MPa. Equation 4 is the general correlation for 150 mm cubes suggested by the manufacturer, from Germann Petersen[26]

standard cubes (the slab was about 1 year old at the time of the tests). This indicates that the main reason for discrepancy is not that the concrete is old (with reduced concrete strength) for the eight railway bridges – at least when the concrete compressive strength is high, that is between 61 MPa and 105 MPa. This is in contradiction to the previous analysis, which found that the pullout test was sensitive to the type of surface it is performed on (however, it is important to remember that this was not an explicit result).

A way to complete the set of data is to use the data from Rockström and Molin[21] – see the triangles in Figure 6. The data come from six road bridges that were aged up to 54 years. Based on these data a regression analysis can be performed. The relationship between the pullout force, F, and the compressive strength of a drilled core with the diameter and height of 100 mm, f_{core} can be modelled with a power function instead of the linear functions used in Figure 2, see Carino.[2] This gives the possibility to model the non-linearities of concrete behaviour in a better way.

Germann Petersen[26] suggests that the following equation could be used as an alternative to Equations 1 and 2

$$f_{\text{cube}} = 0{\cdot}76\,F^{1{\cdot}16}\,(\text{MPa}) \qquad (4)$$

With the data used in this study the following equation is obtained

$$f_{\text{core}} = 0{\cdot}98\,F^{1{\cdot}14}\,(\text{MPa}) \qquad (5)$$

where f_{core} is the calculated compressive strength using a strength relationship between the pullout force and the concrete compressive strength of a core with a diameter and height of 100 mm, in MPa. The regression analysis is based on a power function, $y = ax^b$. The correlation coefficient is 0·97, indicating a relatively strong relationship between the variables. The equation is valid in the interval 11 to 105 MPa. If the two strength relationships are compared it can be seen that Equation 5 gives higher compressive strengths than Equation 4 for the same pullout force.

How to use the proposed strength relationship

There are several ways to use the proposed strength relationship. One way is to determine the characteristic in-situ compressive strength and then in turn establish a compressive strength class for a bridge (e.g. according to EN 13971).[9] Another alternative is to use the calculated mean value, with its dispersion, in a reliability analysis.

Summary and conclusion

The studies in this paper indicate that a pullout method, the pullout test for concrete strength assessment in new structures, can also be used to estimate the in-place concrete strength in old structures such as bridges.

It has been found that the power function relating the compressive strength f_c (MPa) and the pullout force F (kN) given by the manufacturer, $f_c = 0{\cdot}76\,F^{1{\cdot}16}$, give conservative values of the compressive strength f_c. For that reason an improved function is proposed, $f_{\text{core}} = 0{\cdot}98\,F^{1{\cdot}14}$ for the interval 11 to 105 MPa. The proposal is based on tests on eight bridges built between 1965 and 1980, on laboratory tests on a one year old concrete slab and data from Rockström and Molin[21] from six road bridges, which were aged up to 54 years. The results have also been used to analyse the strength of 37 bridges built between 1953 and 1980.

When the pullout test is performed on an old concrete surface, for example an old bridge, caution must be used because there is a risk of a big difference in aggregate size, which could affect the result. In this case more tests should be performed in order to obtain a reliable result.

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