Abstract
A full scale seven-storey reinforced concrete building frame was constructed in-situ in the Building Research Establishment’s Cardington laboratory encompassing a range of different concrete mixes and advanced construction techniques. This provided an opportunity to assess in-situ non-destructive test methods, namely the pull-out test and more specifically the Danish version which has been known as the Lok test, on a systematic basis during the construction of the building. Strength correlations were determined using a power function regression analysis. It is not, however, sufficient to simply average the values of the in-place test results and then compute the equivalent compressive strength by means of this established strength relationship. It is necessary to account for the uncertainties that exist. Interpretation of in-place tests should take into account the uncertainties that exist and therefore should be made by the use of standard statistical procedures. While no procedure has yet been universally accepted, proponents of in-place testing have developed and are using statistically based interpretations. The “tolerance factor approach” and “Carino’s alternative method” have been used for the interpretation of the results and it is shown that the former is resulting in more conservative strength predictions than the latter when the standard deviation of insitu Lok tests is high.

Keywords
In-situ non-destructive tests, strength predictions, pullout tests, strength correlation, statistical analysis

1. INTRODUCTION
In most countries in the world the quality of the concrete in a structure is assessed indirectly by measuring the strength of cubes or cylinders which are made from the concrete
supplied to the site. Whilst this is well accepted by industry, it has its limitations in that problems are seldom detected until it is too late for economic remedial action. This shortcoming could be eliminated by measuring, at an early age, the strength properties of the concrete in-situ. This would also permit an assessment of the effectiveness of surface zone compaction and curing processes and thus provide a more reliable indication of the condition of the finished product. There is also a strong case for measuring the in-situ concrete strength for it may allow much faster “turn-around” for formwork and back-propping, as well as reduced prestressing times [1].

This paper examines work undertaken as part of the European in-situ concrete frame building project which was located in a large airship hangar at Cardington in the UK. This facility was operated as a laboratory by Building Research Establishment Ltd (BRE). The full scale seven-storey in-situ advanced reinforced concrete building frame, designed to Eurocode 2 by Buro Happold, encompassed a range of different mixes, including high strength concretes, and advanced construction techniques. This provided a focus for a number of construction-phase research investigations involving several Universities. These included the project reported in this paper, which was concerned with the capabilities and practicality of use on site of the Lok test, the Danish version of the pull-out test [2]. This paper uses the results from the in-situ concrete frame building project to examine the strength predictions from two statistical methods, namely the “tolerance factor approach” [3] and “Carino’s alternative method” [4].

2. EXPERIMENTAL PROGRAMME

An important feature of the Project was the need to balance the ‘research’ requirements of the Universities involved, with the practical and commercial requirements of the Contractor (Byrne Bros. Ltd) to complete the work with a minimum of delay and disruption. Compromises were necessary on both sides, and one consequence was that limitations were placed upon the number of tests performed. The numbers were relatively small in comparison with those typically associated with laboratory based studies, and in some instances were further curtailed as a result of operational circumstances. In some instances the conflicting requirements of the researchers in the five Universities, involved in the parallel projects, also imposed constraints on the number of tests that were performed.

2.1 Test Methods

Pull-out testing, involving preplanned inserts cast in the concrete, is particularly suitable for direct in-situ measurements of early age strength utilising cut-out panels in shutters where appropriate. The Danish Lok-Test system was selected for this project since this is the version which has gained greatest commercial acceptance worldwide and conforms to ASTM C 900 [2]. One key feature of the pull-out method is the good sensitivity of correlations to compressive strength and the relative insensitivity to mix variables such as aggregate type.

2.2 Scope of Variables

Six different mixes were covered in this study which could be grouped into two strength classes with minimum 28-day characteristic cube strengths of 37 and 85 MPa. The principal variables for the concretes covered by this study were: concrete grade (C37N-10 and C37N-11 with different cement contents and C85), chemical admixtures (plasticiser and superplasticiser) and aggregate type (gravel and limestone).
Tests were performed at different levels of the structure, on columns at different heights (top, middle and bottom), and on slabs, both adjacent to columns and in mid bay (top and bottom). In-situ tests using the Lok-test, were undertaken at 1 day (or as soon as practicable), 3 days, 7 days and 28 days. Results for corresponding air cured 150mm cubes were also made available which permitted the development of Lok-test strength The detailed results of this comprehensive study can be found in a 94 page report published by BRE Ltd [6].

2.3 Data Collection
During the development of the work programme, extensive discussion and pre-planning was undertaken with the staff of BRE. The establishment of good correlations between a measured property and the strength is a key to successful in-situ testing, and for normal practice these should ideally be prepared in advance of the construction starting date. In this case, however, bearing in mind the number of mixes involved, the short time-scale for preparatory work, the BRE intention to set up a laboratory on site, and the need to avoid duplication of effort, correlation specimens were cast on-site during concreting of the structure. In each case these comprised four 200mm timber moulded cubes with four Lok-inserts attached to the vertical sides together with cubes cast using standard 150mm steel moulds which were subsequently tested by a commercial test house (STATS Ltd.) for compressive strength. All the specimens were air-cured adjacent to the building.

3. EXPERIMENTAL RESULTS AND DISCUSSION
The project created a massive amount of data, but equally importantly it provided feedback on the practical issues involved with the application of the Lok-test on site. The strength correlation, determined using power function regression analysis, is presented first. This is followed by a discussion of the in-situ strength predictions obtained using the two statistical methods, i.e. the “tolerance factor approach” [3] and “Carino’s alternative method” [4].

3.1 Lok-Test Strength Correlation
The objective of an in-place test is to obtain an estimate of the properties of concrete in the structure. Very often the desired property is the compressive strength. To make a strength estimation it is thus necessary to have a known relationship between the result of the in-place test and the strength of the concrete for the particular concrete mix concerned. The usual practice in determining the strength relationship is to treat the average values of the replicate air-cured cube compressive strength and in-place test results at each strength level as one data pair. The data pairs are plotted using the in-place test value as the independent value (or X variable) and the compressive strength as the dependent value (or Y variable). Regression analysis is performed on the data pairs to obtain the best-fit estimate of the strength relationship. ACI Committee 228 [8] recommends a rigorous analysis based on the regression analysis of the average of the natural logarithms of the test results at each strength level. For a linear relationship, the equation is as follows:

\[ \ln C = a + b \ln I \]  
\[ C = e^a + I^b \]

Where:

\[ \ln C = \text{average of natural logarithms of compressive strengths,} \]

269
\[ \alpha = \text{intercept of line}, \]
\[ \beta = \text{slope of the line}, \]
\[ \ln I = \text{average of natural logarithms of in-place test results}. \]

By obtaining the anti-logarithm of \( \ln C \), the above equation is transformed into a power function. This not only allows for a non-linear strength relationship, if such a relationship is needed, but it also satisfies one of the underlying assumptions of the ordinary least squares method of analysis (constant error in the \( Y \) value). It is generally accepted that the within-test variability of standard cylinder or cube compression tests is described by a constant coefficient of variation. Therefore, the standard deviation increases with increasing compressive strength. It follows that by taking the natural logarithms of groups of test results, which have the same coefficient of variation, the standard deviations of the logarithm values in each group will have the same value. The calculations for this more rigorous procedure are outlined in the ACI Committee 228 report [8].

The relationship obtained with the above procedure, shown graphically in Figure 1, has a surprising similarity with the linear manufacturer’s recommended correlation for strengths in the range 5 to 40 MPa. It is only above the compressive strength of 40 MPa that the two correlations appear to deviate from each other resulting in a difference of 16 MPa at the Lok force of 60 kN. The linear manufacturer’s correlation gives the lower value of 86 MPa compared to 102 MPa estimated by the power function. Price & Hynes [9] have suggested that (a) pull-out tests become less sensitive to changes in compressive strength at high strength levels, and (b) strength correlations obtained for high strength concretes show increasing divergence from the manufacturer’s recommended correlation at higher strength levels.

![Figure 1: Lok test strength correlation based on a power function.](image-url)
levels [9]. Based on this it was felt that the power function relationship was the more realistic one to use for the whole range of mixes used for the European Reinforced Concrete Building project. The wisdom of assuming that all the data obtained from the different mixes belong to one population, to give a strength relationship which is close to the true one, can only be tested in the context of the overall in-situ strength estimates.

3.2 Lok-test strength estimates

The strength correlations determined in the previous section have been used to estimate the in-situ strengths based on measurements on the structure. A note of caution is necessary; it is not sufficient to simply average the values of the in-place test results and then compute the equivalent compressive strength by means of the previously established strength relationship. It is necessary to account for the uncertainties that exist. Interpretation of in-place tests should be made by the use of standard statistical procedures [8]. While no procedure has yet been universally accepted, proponents of in-place testing have developed and are using statistically based interpretations. ACI Committee 228 [8] has reviewed four statistical methods for evaluating in-place test results. Two suggested methods have been selected for determining the lower tenth percentile of strength, (i.e. the probability of obtaining a test with strength less than this is approximately 10 percent – note that the norm for the UK is 5 percent), with a prescribed confidence level, based on nondestructive tests of concrete.

3.3 The “Tolerance Factor Approach” [3]

The estimate of the tenth percentile strength \( Y_{0.10} \) can be determined, for a normal distribution function, as follows [8]:

\[
Y_{0.10} = Y - K_s
\]

where:

- \( Y_{0.10} \) = lower tenth percentile of strength (i.e. 10% defective)
- \( Y \) = sample average strength
- \( K \) = one-sided tolerance factor, and,
- \( s_Y \) = sample standard deviation.

The tolerance factor is determined from statistical characteristics of the normal probability distribution and depends on the number of tests \( n \), the confidence level, and the defect percentage. Values of \( K \) can be found in reference books for statistics. Figure 2 shows how the \( K \) value varies with the number of tests performed on site but also with the required confidence level. BS EN 13791:2008 Assessment of in-situ compressive strength in structures and precast concrete components [10] adopted a similar procedure to the tolerance factor but with \( K = 1.48 \), irrespective of number of tests. A 95% confidence level has been selected for the analysis of the Cardington results so that it can be compared with the Carino’s alternative method. It must however be noted that Hindo and Bergstrom suggested that only 75% is used for ordinary structures, 90% for very important buildings, and 95% for crucial parts of nuclear power plants. It is obvious that as the variability of the test results increases or as fewer tests are performed, the tenth-percentile strength is a smaller fraction of the sample average strength. This also results in a large scatter of predicted lower tenth percentile strengths, see Figure 3. Two criticisms for this method are [8]: (a) the strength relationship is presumed to have no error; and, (b) the variability of the compressive strength in the structure is assumed
Figure 2: One-sided tolerance factor for 10% defective level

Figure 3: Tenth-percentile strength determined from the “tolerance factor method”
to be equal to the variability of the in-place test results. While the second factor will make the estimates overly conservative, the first factor will have the opposite effect [8]. This method is simple to use, requiring only tabulated statistical factors and a calculator, but because its underlying assumptions have been questioned, a rigorous method has been proposed.

3.4 “Carino’s alternative method” [4]

The rigorous method is more complex and requires an electronic spreadsheet or computer program for practical implementation. The values obtained from the correlation tests, i.e. Lok tests and cube compressive strengths, are used to compute the lower confidence limit \( Y_{\text{low}} \), i.e. the desired confidence level has been taken to be 95%) of any estimates to be undertaken with the use of this correlation, see Figure 4. This has been computed using error of fit given by Mandel’s procedure [12], the standard deviation of the estimated value of compressive strength given by Stone and Reeve’s procedure [13], and the student t-value for \( m \) (the number of replicate Lok tests) obtained from Natrelle [11]. The lower confidence limit for the average concrete strength is then obtained from the equation [8]:

\[
Y_{\text{low}} = Y - (t_{m-1,n} \cdot s_Y)
\]  

where:

- \( Y_{\text{low}} \) = lower confidence limit at 95% confidence level;
- \( t_{m-1,n} \cdot s_Y \) = student t-value for \( m-1 \) degrees of freedom and 95% confidence level;
- \( m \) = the number of replicate Lok tests.

![Figure 4: \( Y_{\text{low}} \) and \( Y_{0.10} \) determined with “Carino’s alternative approach”](image-url)
The tenth-percentile strength ($Y_{0.10}$) is then computed from [8]:

$$Y_{0.10} = Y_{low} - 1.282s_{cf}$$  \hspace{1cm} (4)

where $s_{cf}$ is the standard deviation of the logarithm of concrete strength in the structure and is obtained from the assumption that the ratio of the standard deviation of compressive strength to the standard deviation of Lok tests in the field is the same as that obtained during the laboratory correlation testing. This equation accounts for the variability of the insitu compressive strength, i.e. it converts the average insitu strength to a characteristic strength, see Figure 4.

### 3.5 Comparison of the two statistical methods

The predicted tenth percentile strengths by the two methods are compared in Figure 5. Carino’s alternative method appears to give more weight to the uncertainty in determining the strength correlation and less weight in the standard deviation of insitu Lok tests. Consequently the predicted strengths are not scattered and this may justify doing a regression analysis through the data to get an indicative percentage of the ratio of tenth-percentile strength to estimated average insitu strength. The tenth-percentile strength is around 80% of the estimated average insitu strength. The same cannot be justified for the tolerance factor approach as the predicted tenth-percentile values appear to be scattered a lot more; this arising from the fact that this procedure does not include the uncertainty of the determined strength.

---

**Figure 5: Comparison of the tenth-percentile strengths estimated from the “tolerance factor approach” and “Carino’s alternative approach”**
correlation but relies exclusively on the standard deviation of insitu Lok test values. The regression line through the data indicates that the tolerance factor approach gives lower, and therefore more conservative, strength estimates than Carino’s alternative method. However, this generalization is not justified because of the scatter of predicted strengths. Table 2 shows that when the standard deviation of insitu Lok tests is low then the two methods predict similar tenth-percentile strengths. However, when the standard deviation is high then the tolerance factor approach will give a much lower value than Carino’s alternative method.

4. CONCLUSIONS

Data obtained during the construction of a full scale seven-storey in-situ reinforced concrete building have been used to clarify some issues regarding the interpretation of pull-out test results. The main conclusions are:

− There are definite advantages in being able to rely on the manufacturer’s recommended strength correlation, as was the case with the Lok tests, in the absence of a specific strength correlation.

− Power function regression analysis appears to be more suitable for deriving a general correlation for the full range of concrete strengths, including high strength concretes, likely to be encountered on site. The general correlations derived with linear and non-linear regression are almost identical for strengths in the range 5 to 50 MPa. The power function correlation however is able to take into account the reduction in sensitivity to changes in compressive strength above 50 MPa.

− Statistical procedures should be used to interpret Lok-test data. It is not sufficient to simply average the values of the Lok-test results and then compute the equivalent compressive strength by means of a previously established strength correlation.

− The tenth-percentile strengths estimated by the tolerance factor method are lower than the ones estimated with Carino’s alternative method when the standard deviation of insitu Lok-tests is high.

− Experimental field studies are needed to compare the tenth-percentile strengths estimated by these methods with the values obtained from many core tests. Only then can the reliability of these methods be evaluated.

There is, in terms of the unlikely event of contractual disputes regarding quality, an added complication even after having estimated the tenth-percentile strength. Based on ACI 318 [14]: “if the average compressive strength of three cores exceeds 85% of the specified compressive strength and no single core strength is less than 75% of the specified strength, then the concrete strength is deemed to be acceptable”. There were, until the publication of BS EN 13791:2007 [10], no analogous acceptance criteria for the estimated insitu compressive strength that is based on Lok-tests [8].

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the helpful collaboration of the Building Research Establishment, Byrne Bros., and Ready Mixed Concrete Ltd. The successful onsite testing for this project was carried out by Dr. G. D. Henderson and this is gratefully acknowledged. The authors are also very grateful for the extensive advice received, during and after the project, from Prof. T. Harrison (Quarry Products Association, UK) and Mr. J. A. Bickley (Bickley Associates Ltd, Canada).
REFERENCES

[8] ACI Committee 228, ‘In-Place Methods For Determination Of Strength Of Concrete’, Technical Committee Document 228.1R-03, (American Concrete Institute, PO Box 19150, Detroit, MI 48219, 2003).