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Deflection Measurement Considerations in Evaluating FRC Performance Using ASTM C 1018

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Synopsis: The issue of how the method of determining midspan deflection in ASTM C1018 toughness tests influences first-crack strength, first-crack deflection, toughness indices and residual strength factors is addressed by comparing results obtained using the method now required in the current standard, which is based on net midspan deflection determined as the nominal midspan deflection minus the average of the deflections measured at the beam supports, with corresponding same-specimen results based on nominal midspan deflection only which was not explicitly excluded in earlier versions of the standard. The problem of dealing with the portion of load-deflection relationship immediately after first crack when it is unstable is also discussed.

The range of test specimens for which comparative data are reported includes a series of third-point-loaded 500x150x150 mm beams with three different steel fibers ranging in length from 18 mm to 63 mm, and a second smaller series of 350x100x100 mm beams that allows for assessment of the effects of beam size and fiber alignment. Fiber contents vary from 20 to 75 kg/m^3 (0.25 to 0.94% by volume). Also included is a series of 350x100x100 mm beams with a single type of fibrillated polypropylene fiber of length 38 to 64 mm in amounts of 0.5 to 0.75% by volume.

The results illustrate the extent to which the C1018 parameters I_5, I_{10}, I_{20}, $R_{5,10}$, and $R_{10,20}$ are effective in distinguishing the performance of the various FRC mixtures in terms of fiber type, geometry and amount. The index I_5 is found to be least effective and a case is made for greater emphasis on use of residual strength factors, especially $R_{10,20}$, when employing the test to specify and control the quality of FRC.

Keywords: Beams (supports); cracking (fracturing); deflection; fiber reinforced concretes; fibers; polypropylene fibers; strength; tests; toughness

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INTRODUCTION

The issues of exactly how deflection should be measured and the possible effects of different methods of determining deflection on the load-deflection relationship and the toughness parameters derived from it have been the subject of much discussion and some controversy since ASTM C1018(1) was first introduced in 1984.

Since 1984 the Apparatus section of the standard has required deflection-measuring equipment to "accurately determine the net deflection of the specimen under load exclusive of any effects due to seating or twisting of the specimen on its supports, and the Procedure section of the standard has included the imperative statement in mandatory language "Exercise care to ensure that the measured deflections are the net values exclusive of any extraneous effects due to seating or twisting of the specimen on its supports or deformation of the support system". While the intent of these statements was clear enough, the specifics of how it might be met were contained in a non-mandatory note recommending the use of additional deflection-measuring devices at each beam support. The 1984, 1985, 1989 and 1992 editions of the note also acknowledged that the increased number of deflection-measuring devices makes the processing of data to obtain average net deflection more complex and stated that a recommended correction procedure for drawing a tangent to the initially concave upwards portion of the load-deflection curve "allows the net deflection to be obtained reasonably accurately."

In a 1985 state-of-the-art paper on toughness(2), the writer questioned whether deflection measurement at the midspan only, termed nominal deflection, was "reasonably accurate" and showed that it was in fact largely responsible for the wide variation in midspan deflections at first crack reported in various publications available at the time. The paper also illustrated the effect on toughness indices for same-specimen load-deflection relationships obtained using net and nominal midspan deflection measurement (Fig. 1), and acknowledged that nominal deflection measurement at the midspan was a common and imperfect compromise which is simpler and more convenient for routine use than net deflection measurement requiring additional deflection-measuring devices at the supports along with calculations to average the beam support deflections and subtract the average from the midspan deflection.

Unfortunately, the notion conveyed by the note in the 1984 and 1985 editions of ASTM C1018 that nominal deflection measurement was reasonably accurate and good enough for most testing was widely believed until well after 1985. However, in the 1989 edition the standard was modified to delete reference to this notion and replace it with wording stating that "Nominal deflections based only on midspan measurements may be much larger than corresponding net midspan deflections obtained by subtracting the average of the deflections measured at the two supports from the corresponding nominal deflection at the midspan". Also added was the comment that "Toughness indices based on nominal midspan deflections may be less than the equivalents calculated using net midspan deflection". This non-mandatory language stating the desirability of deflection measurement at the supports as well as the midspan and the possibly significant effect on toughness indices remained unaltered in the 1992 edition of ASTM C1018.

In 1994 the standard was modified to delete all reference to testing based on nominal midspan deflection measurement thus making even more explicit the requirement to determine net deflection and to compute toughness indices and residual strength factors solely on that basis. Detailed descriptions with photographs of two alternative deflection-measuring systems for doing so were added, and a formula for estimating the first-crack deflection in terms of the size of the test specimen and the modulus of the concrete was introduced to help users confirm the validity of deflection measurements.

Like most ASTM Standards, ASTM C1018 has evolved through consensus and compromise between those who advocated the need for net deflection measurement despite increased experimental complexity and those who argued for permitting nominal deflection measurement because of experimental simplicity and practicality. Naturally, fewer laboratories had the more complex equipment needed to determine net midspan deflection, and those that did not have it tended to test specimens using nominal deflection measurement despite failing to comply with the intent of the standard. For example, in an interlaboratory comparison of data(3), supposedly obtained according to ASTM C1018-89, only four of six participants measured net midspan deflection while the two others measured nominal deflection.

Despite much discussion and some controversy over the issue of deflection measurement, there is little published data comparing results obtained using net deflection measurement with those obtained using nominal deflection measurement. This paper makes same-specimen comparisons for a variety of steel and polypropylene fibers at different fiber contents. The results reflect the evolution of ASTM C1018 from 1984 when only toughness indices I_5 and I_{10} and the ratio I_{10}/I_5 were reported, to 1989 when the residual strength factor $R_{5,10}$ became a requirement and the index I_{20} was highlighted instead of I_{30} as a first option along with the residual strength factor $R_{10,20}$. This followed introduction of the concept of residual strength factor in 1986(4).

Since the validity and accuracy of deflection measurements influences the values of toughness indices (Fig. 1) along with the values of residual strength factors derived from them, the issue of how effective the various ASTM C1018 parameters are in distinguishing the performance of FRC's in terms of fiber type, geometry and content is also addressed in the paper. This issue is also a subject of much discussion and some controversy since the standard has been used in specifications to assess FRC performance using parameters ranging from the lowest permissible end-point deflection criterion and toughness index, I_5, to higher end-point deflection criteria and corresponding residual strength factors, such as $R_{10,50}$. The merits of low-end point versus higher end-point deflections and the significance of toughness indices versus residual strength factors can also depend on the response of the testing system. The discussion also deals with the effect of the testing system response rate on the load-deflection function immediately following first crack when there is sometimes a rapid and unstable decrease in load and increase in deflection, particularly for low fiber contents.

EXPERIMENTAL PROGRAM

In the first set of tests reported, the fiber distributor who sponsored the tests in 1987 wished to compare the performance of several types of steel fiber available in Canada in the context primarily of the relatively low fiber contents and low to medium strength concrete matrices associated with industrial floor slab applications. In choosing the specimen size it was recognized that stiff fibers of length 50 to 63 mm would be subject to significant preferential fiber alignment if evaluated using 300x100x100 mm beams and that the ASTM C1018 requirement for thick sections that the minimum specimen dimension be at least 3 times the fiber length would be severely violated. In order to obtain results more representative of thick sections and meet more closely the specimen size/fiber length minimum of 3, the heavier less convenient 450x150x150 mm beam size was employed in the majority of the tests, although additional 300x100x100 mm beams were tested in two cases to get an idea of the effect of specimen size and associated preferential fiber alignment on test results.

In the second set of tests also in 1987 another fiber distributor who wished to evaluate the performance of fibrillated polypropylene fibers of length 38 to 64 mm chose the more economical 350x100x100 mm specimen size recognizing that flexible polypropylene fibers would probably be less subject to the effects of preferential fiber alignment.

Both sponsors selected specific fiber types, lengths and amounts to be evaluated in concretes of specified strength 25 MPa or 30 MPa as shown in Tables 1 and 2, and both wished to have the tests conducted with deflection measured strictly in accordance with intent of C1018-85 "that the measured deflections are the net values exclusive of any extraneous effects due to seating or twisting of the specimen on its supports or deformation of the support system". This was accomplished using the 3-transducer arrangement (Fig. 2), now included in the 1994 edition of ASTM C1018, in which the deflection reproduced on the x-y plotter is the net deflection obtained by subtracting the voltage representing average of the deflections at each beam support from the voltage representing the midspan deflection. However, since the writer was also interested in comparing net deflection with nominal midspan deflection and in the associated comparison of toughness parameters, an additional x-y plotter was added to allow same-specimen plots of load versus net deflection and load versus nominal deflection. Sets of four specimens were tested for each fiber-matrix combination, and the results in Tables 1 and 2 are the mean values for each set calculated in accordance with C1018-89 for toughness indices I_5, I_{10} and I_{20} and residual strength factors $R_{5,10}$ and $R_{10,20}$. Values based on net deflection measurement are in bold print while those based on nominal deflection are in normal print.

DISCUSSION OF RESULTS

The discussion is confined to toughness indices (I) and residual strength factors (R). First-crack parameters are included in Table 1 and 2. Generally, first-crack deflections for nominal deflection measurement are 2.8 to 3.2 times larger than corresponding values for net deflection measurement, while first-crack strengths are essentially equal for both methods of deflection measurement.

Effect of Deflection-Measuring Technique

The effect on I and R values of calculating them on the basis of net deflection versus calculating them on the basis of nominal deflection varies with fiber type, geometry and amount as illustrated by the specimen examples in Fig. 3 and 4.

Starting with 450x150x150 mm beams, the three relationships for steel fibers in Fig. 3 illustrate the main possibilities.

The case of gradual stable strain-softening after first crack (Fig. 3a) is perhaps the easiest to explain because of its approximately constant slope. In this case, values of toughness indices denoted by I' are derived from the relationship obtained using nominal midspan deflection (broken line in all figures), and they are less than the indices denoted by I determined in the proper way from the relationship obtained using net midspan deflection (solid line in all figures). Clearly, this results from the fact that the average vertical ordinate for the total area representing the numerator in any index decreases as the end-point deflection moves to the right, making this ordinate for any end point on the broken line less than the ordinate for the corresponding end point on the solid line, while the horizontal abscissae for the numerator representing total areas and the denominator representing first-crack areas remain in the same proportion for both broken and solid lines. Thus, I_5', I_{10}' and I_{20}' are less respectively than I_5, I_{10} and I_{20}. Likewise, residual strength factors, which are in fact the average ordinate between consecutive end-points divided by the first-crack ordinate, decrease as the end points move to the right, so $R'_{5,10}$ and $R'_{10,20}$ are less respectively than $R_{5,10}$ and $R_{10,20}$

Considering the special case of elastic-plastic behaviour where both broken and solid lines are horizontal from first crack, it should readily be understood that I' and R' values will be the same as I and R values because the vertical ordinate remains the same for all parameters. Extending the analysis to the case of gradual stable strain-hardening where the ordinate actually increases as the end-point deflection moves to the right (Fig. 3b), it is expected that I' and R' values will exceed I and R values. This situation is relatively uncommon, but is known to happen for certain type-amount combinations of hooked-end fibers as in Fig. 3b.

The third case is unstable strain-softening immediately after first crack followed by stable nearly plastic behaviour thereafter (Fig. 3c). In these cases the average vertical ordinate for total area is again less for the broken line relationship than for the solid line one, so I' values are less than I values. However, when the portions of the relationships between consecutive end points used to calculate R' and R values are horizontal (plastic) R' and R values may be nearly equal, for example $R'_{5,10}$ and $R_{5,10}$ in Fig. 3c.

Similar situations arise with the 300x100x100 mm beams. For example, with steel fibers (Fig. 4a) the extensive plastic portion of both relationships following first crack accounts first for $R_{10,20}$ almost equal to $R_{5,10}$ and second for $R'_{5,10}$ almost equal to $R_{5,10}$. Polypropylene fibers (Fig. 4b) can also give rise to the situation where I' values are much less I values while R' and R values are not substantially different.

Effect of Unstable Strain-Softening Immediately After First Crack

Some fiber type-amount combinations, particularly those using low fiber contents, are associated with a rapid decrease in load and increase in deflection immediately after first crack which occurs so quickly that the response rate of the load and deflection-recording system may not be fast enough to reflect what is really happening. The relationships in Fig. 3c and 4b are examples typically obtained under open loop control conditions.

Part of Fig. 3c enlarged to highlight the unstable region immediately following first crack is shown as Fig. 5a. The unstable region in question is AY in general, although a portion of it, AX, appears stable initially from the clearly defined track of the pen on the plotter, while the portion XY is poorly defined with only a faint linear pen track. In Fig. 5b the transition corresponding to the change in slope (specimen stiffness) at X is not discernible and the whole of AY is likely unstable. In the limiting case of concrete without fibers, the beam breaks suddenly at A and has no residual strength thereafter, so the load drops instantaneously to zero before deflection can increase, AZB in Fig. 5, even though the plotter records a line somewhere between AXY and AZB. The same behavior applies at very low fiber contents. With sufficient fibers there is a deflection increase as the load drops from first crack to the residual value that can be sustained stably over a period of time, as depicted by the portion of the load-deflection relationship to the right of Y. Dealing with uncertainty regarding the position of AY which could be anywhere between AXY and AZY is the problem. Obviously, the same issue arises with regard to A'Y' (Fig. 5) for nominal deflection measurement.

Toughness indices calculated in the normal way using AXY will obviously decrease if recalculated using AZY. In Fig. 5a the effect will be greatest for I_5, derived from the area AXYCDB, and relatively less for I_{10}, derived from AXYEFB in which the portion CEFD is unaffected by the position of AY, and of course less still for I_{20}. Perhaps the most important point is that $R_{5,10}$, which is based only on the area CEFD, is unaffected by any uncertainty in the position of AY because C is the right of Y, and likewise $R_{10,20}$ (CC63 fibres in Table 3). This applies also to Fig. 4a. However, in Fig. 5b the effect of uncertainty regarding the position of AY extends to $R_{5,10}$ because the area CEFD is affected since C is left of Y. Nevertheless, $R_{10,20}$ which is based on the area to the right of EF is unaffected (EE18 fibres in Table 3). This applies also to Fig. 3a, 3b and 4b, but Fig. 5b represents the worst case observed for the data set in terms of C being furthest to the left of Y.

Since the position of the unstable portion of the load-deflection relationship AXY is probably influenced by both the response rate of the data-recording system and the stiffness of the testing frame and that of the specimen, an approach to performance assessment that eliminates this uncertainty is desirable. Thus, it is imperative that the widely practised tendency to highlight I_5, which is most severely affected, and not consider parameters which are less affected, such as I_{20}, or usually not affected at all, such as $R_{10,20}$, must change. Reaching the conclusion in the 1991 interlaboratory study (3) that "ASTM C1018 toughness indices are observed to be relatively insensitive to fiber type, volume fraction and specimen size", while highlighting I_5 and ignoring R values in the published analysis, despite the fact that reporting of $R_{5,10}$ was mandatory in the 1989 edition of the standard and $R_{10,20}$ was identified as optional, presented an incomplete impression of the effectiveness of ASTM C1018 for distinguishing performance in terms of fiber parameters.

Effectiveness of C1018 Parameters in Distinguishing FRC Performance

While the five single-specimen examples in Fig. 3 and 4 permit differences in performance to be distinguished in terms of the appearance of the load-deflection relationships and the numerical values of parameters such as I_{20} (range 10.2 to 17.3) and $R_{10,20}$ (range 38 to 87), the effects of variables like fiber geometry, amount and specimen size are best distinguished using the mean values from Tables 1 and 2 plotted graphically as in Fig. 6 for toughness indices and in Fig. 7 for residual strength factors. To make the indices graphically comparable, the scales for I_5, I_{10}, and I_{20} are chosen to correspond to the values of 5, 10 and 20 corresponding to elastic-plastic or yield-like behavior which is the reference level against which actual performance is usually compared (Appendix XI of ASTM C1018). Accordingly, the I_5 scale is twice as large as the I_{10} scale and four times as large as the I_{20} scale. Naturally, $R_{5,10}$ and $R_{10,20}$ are plotted to the same scale as they both have the same range of 0 to 100.

Effect of Fiber Geometry and Amount--Three varieties of steel fibers designated CC63, EE18 and HE50 are compared in terms of fiber content for 450x150x150 mm beams (Fig. 6 and 7). A fourth, CW60, is included at one fiber content. Both the solid line trends (based on net deflection) and the broken line trends (based on nominal deflection) are definitive in illustrating the importance of fiber content, but the values in the latter case are lower except for some HE50 concretes consistent with the reasoning given earlier in discussing Fig. 3 and 4. Subsequent discussion is limited to the solid line trends which represent proper accurate measurement of deflection. However, they are subject to the uncertainty associated with the unstable AXY (Fig. 5) portion of the load-deflection relationship, especially for low fiber contents, the effect of which is to decrease some I values, particularly I_5, below the values plotted.

Since the graphs for toughness indices (Fig. 6) are scaled vertically to make the I_5, I_{10}, and I_{20} values graphically comparable, the steeper the slope the better the distinction of performance in terms of fiber content. Clearly, I_5 is least effective and

I_{20} is the most effective with I_{10} almost as effective as I_{20}. In terms of residual strength (Fig. 7), both $R_{5,10}$ and $R_{10,20}$ appear effective in making the distinction by fiber content. However, $R_{10,20}$ is in fact better because the uncertainty associated with the unstable AXY portion (Fig. 5) of the load-deflection relationship which influences some $R_{5,10}$ values at low fiber contents is without exception eliminated for $R_{10,20}$.

The importance of fiber geometry for steel fibers reflects the influence of aspect ratio and improvements to pullout resistance by use of crimping (CC and CW) and hooked ends (HE) or enlarged ends (EE). For example, at 0.5% by volume or 40 kg/m^3 of fibers $R_{10,20}$ values are about 88 for HE 50, 82 for CW 60, 62 for CC 63 and 42 for EE 18 over a range of aspect ratio of 100 for HE 50 fibers to 38 for EE 18 fibers.

Concrete matrix strength within the limited 25 to 30 MPa range examined has little influence on I or R values.

Effect of Fiber Type and Amount--Steel and polypropylene fibers are compared in terms of fiber content for 300x100x100 mm beams (Fig. 8 and 9 left). Differences between the solid line trends (based on net deflection) and the broken line trends (based on nominal deflection) are similar to those in Fig. 6 and 7, and are consistent with the reasoning given earlier in discussing Fig. 3 and 4. Only the solid line trends are discussed further.

Once again, the manner in which the graphs in Fig. 8 are scaled means that slope is an indicator of the effectiveness of each toughness index in distinguishing performance. Clearly, I_{20} and I_{10} are again more effective for this purpose than I_5 (Fig. 8 left), just as in Fig. 6. For residual strength, $R_{5,10}$ and $R_{10,20}$ are both effective (Fig. 9 left), and illustrate the expected influence of fiber content and in the case of the polypropylene fibers the effect of length or aspect ratio. For example, at 0.5% by volume of fibers the $R_{10,20}$ values are about 80 for the CC 63 steel fiber, 37 to 39 the FP 38 and FP 64 polypropylene, and, by interpolation on Fig. 7, for the EE 18 fiber about 42 plus a small amount attributable to specimen size effect (see next section).

Effect of Specimen Size--From the limited data available, a significant increase in both I and R values is associated with reducing beam size from 450x150x150 mm to 300x100x100 mm for the long stiff CC 63 steel fibers when preferential fiber alignment by the mold surfaces is significant (Fig. 8 and 9, right). This is to be expected since the ratio of specimen cross-section to fiber length is 1.6 compared with the minimum of 3 required for thick sections in ASTM C1018. For the shorter EE 18 fiber, where the corresponding ratio is 5.3, the fiber alignment effect is probably minimal as suggested by the comparison at 75 kg/m^3. This is consistent with the results of an earlier study (5) to examine the effect of preferential fiber alignment on test results using fibers of length 76 mm and 25 mm in molded and sawn specimens of 100 mm cross-section.

Precision of Results

Within-batch coefficients of variation for each set of four specimens are given in Tables 4 and 5 for the two different specimen sizes.

While there is no conclusive link between the individual values in terms of fiber type, geometry or amount, the highest values are associated mainly with low fiber contents of CC63 steel fibers. These are the largest in individual size. At low fiber contents this means the lowest number of fibers per unit volume of concrete, which may contribute to more marked nonuniformity in the fiber distribution and a more variable FRC than for the other fibers.

The most meaningful numbers are the mean values which indicate the level of precision that should be expected on average when testing multiple sets of specimens. In this regard, there are no major differences for the two specimen sizes, which if combined total 24 sets, and it is clear that the parameters which it has been argued should be highlighted more in future testing, that is I_{20}, $R_{5,10}$, and $R_{10,20}$, can be evaluated with reasonable precision. The highest mean within-batch coefficient of variation is about 13% for $R_{10,20}$ and 19 of 24 values are less than 18%. It must be recognized than the higher the end-point deflection the greater the variability of the results, but in view of the arguments previously discussed it is pointless to rely on I_5 determinations simply because of better precision.

The mean values reported in Tables 4 and 5 compare closely with values for another recent data set (6) analyzed in the same way for 300x100x100 mm beams tested at various ages and machine stroke rates.

CONCLUSIONS

1. Effectively utilizing ASTM C1018 to evaluate the performance of FRC and distinguish the importance of the material type, geometry and amount of the fibers depends on recognition of the following limitations:

   (i) Toughness indices and residual strength factors derived using nominal deflection measurement are usually less, often considerably less, than values derived using net deflection measurement as required by the standard. However, there are exceptions where nominal deflection measurement may produce values equal to or slightly more than values obtained according to the standard.

   (ii) Some fiber-matrix combinations, particularly with low fiber contents, exhibit rapid load decrease with deflection increase after first crack that is unstable and may not be detected accurately by the load and deflection-recording system. The uncertainty associated with this unstable portion of the relationship affects the toughness index I_5 most severely, and its effect lessens with increasing end-point deflection, and is usually quite small for I_{20} and higher deflection indices. Evaluating performance in terms of residual strength factors can eliminate the effect of this uncertainty entirely when using $R_{10,20}$, and the effect on $R_{5,10}$ is often quite minimal. It exists when C or E are to the left of Y in Fig. 5 and is eliminated when C and E are to the right of Y in Fig. 5.

(iii) The use of the preferred 300x100x100 mm beam with long rigid fibers like steel tends to produce toughness indices and residual strength factors greater than for otherwise comparable 450x150x150 mm beams.

2. The data set discussed in the paper which is based on 22 fiber-matrix combinations and 88 tests demonstrates that some ASTM C1018 parameters are more effective than others for distinguishing the effects of fiber type, geometry and amount on the performance. The index I_5 is certainly least effective. Both I_{10} and I_{20} (which is a required test parameter in the 1994 standard) are much more effective.

   The index I_{20} is least influenced by uncertainty regarding the position of the portion of the load-deflection immediately following first crack in cases where rapid unstable behaviour occurs. The fact that the effect of this uncertainty can be minimized or eliminated entirely by calculating residual strength factors, coupled with the fact that these factors are more easily understood than toughness indices and have more potential for direct application in strength-based design (7), is an argument for less emphasis on I values and more emphasis on R values, particularly $R_{10,20}$, in using the test method to specify and control the quality of FRC. Certainly, it is imperative that the widely practised tendency to highlight I_5 and ignore $R_{5,10}$ and $R_{10,20}$ must change.

3. The conclusion that parameters such as I_{20} and $R_{10,20}$, and to a slightly lesser degree I_{10} and $R_{5,10}$, are effective in distinguishing performance differences by fiber type, geometry and amount is not unique to these two series of specimens or to the particular equipment used. Similar results were reported (8) in the same format as Fig. 6, 7, 8 and 9 for a series of 108 tests on 18 steel fiber-matrix combinations performance on different equipment using 750x150x100 mm beams and supervised by the writer in Stockholm in 1989. However, both investigations employed the 3-transducer deflection-measuring system (Fig. 2) rather than the rectangular jig arrangement identified as an alternative in the 1994 edition of ASTM C1018.

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