ANALYTICAL REVIEW ON FLEXURAL TOUGHNESS OF FIBER REINFORCED CONCRETE

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Abstract: The development of fiber reinforced concrete, which improves some lacks of normal concrete performance, gives great contribution in the future of structural application. Compared to plain concrete, fiber reinforced concrete has some mechanical properties advantages such as: ductility that correspond to energy absorption, impact resistant, tensile and flexural strength, fatigue life, shrinkage, abrasion, fragmentation, and spalling. It should be noticed that the fiber addition will improve the bending resistance and ductility of concrete. Some methods of testing and calculating of flexural toughness have been adopted by various users. There are some limitations in current techniques of toughness characterization. An important consideration should be attempted in analyzing and implementing the methods of testing and evaluating of the flexural toughness of steel fiber reinforced concrete for better accuracy and flexibility in application. This paper wants to review, compare, and discuss about some flexural toughness of fiber reinforced concrete evaluation methods, such as ACI Committee 544, ASTM C 1018, CMOD, ASTM C 1399, and also the PCSm method. According to the limitations of the methods mentioned above, the PCSm method is suggested to become a simpler and more appropriate one.

Keywords: flexural, toughness, fiber reinforced concrete, method

Abstrak: *Perkembangan beton serat, yang mengatasi beberapa kekurangan dari kinerja beton normal, memberikan kontribusi penting dalam aplikasi struktur di masa depan. Dibandingkan dengan beton normal, beton serat memiliki beberapa keungggulan sifat-sifat mekanis seperti: daktilitas yang berhubungan dengan penyerapan energi, ketahanan impak, kekuatan tarik dan lentur, ketahanan fatik, susut, abrasi, fragmentasi dan pengelupasan. Penting untuk dicatat bahwa penambahan serat akan meningkatkan ketahanan lentur dan daktilitas beton. Beberapa metode pengujian dan perhitungan keliatan lentur telah diadopsi oleh berbagai kalangan, namun sangat disadari bahwa terdapat keterbatasan dalam hal karakterisasi keliatan pada teknik-teknik yang ada saat ini. Analisis dan implementasi dari metode pengujian dan perhitungan keliatan lentur pada beton berserat baja perlu mendapat perhatian agar diperoleh aplikasi yang akurat dan fleksibel. Makalah ini ingin mengkaji, membandingkan, dan mendiskusikan beberapa metode evaluasi keliatan lentur pada beton berserat baja, seperti ACI Committee 544, ASTM C 1018, CMOD, ASTM C 1399, dan metode PCSm. Hasil kajian beberapa metode tersebut di atas mengusulkan metode PCSm sebagai metode yang lebih sederhana dan tepat untuk evaluasi keliatan lentur pada beton berserat baja.*

Kata kunci*: lentur, keliatan, beton serat, metode*

INTRODUCTION

The progress of concrete technology has shown a promising advance in last decades since the first implementation of natural fibers into Egyptian mud bricks and also Chinese and Japanese housing construction (Li, 2002). Concrete, that is very brittle, lose their tensile load-carrying capacity as soon as the matrix crack formation (Fischer and Li, 2004). According to Fischer and Li (2004), the addition of fibers in concrete will increase the toughness of the cementitious matrices; however, their tensile strength and strain capacity beyond first cracking are not enhanced. It is also emphasized that the development of fiber reinforced concrete, which improves some deficiencies of normal concrete performance, gives great contribution in the future of structural application. According to the definition of ACI Committee 544.1R-82 (ACI, 1978b), fiber reinforced concrete is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete fibers. Fibers can be produced from steel, plastic, and natural materials in various shapes and sizes.

In the beginning, it was assumed that tensile and flexural strength of concrete can be substantially increased by introducing closely spaced fibers which would obstruct the propagation of micro cracks, therefore delaying the onset of tension cracks and increasing the tensile strength of material (Mehta and Montwieo, 1993). However, some experimental studies have shown that the volumes and sizes of fibers of conventional mortars or concretes did not show a substantial improvement of mixtures without fiber. The researchers found a considerable improvement of post-cracking behavior of fiber concrete. It can be said that compared to plain concrete, fiber reinforced concrete has some mechanical properties advantages such as: ductility that correspond to energy absorption, impact resistant, tensile and flexural strength, fatigue life, shrinkage, abrasion, fragmentation, and spalling (Balaguru and Shah, 1992).

Unlike plain concrete, a fiber concrete specimen doesn't break immediately after initiation of the first crack shown by typical load-deflection curve (Mehta and Monteiro, 1993). It influences the work of fracture, which is referred to as toughness, and is represented by the area under the load-deflection curve. According to ACI (1978a), the total energy absorbed by the area under the load-deflection curve before complete separation of a beam is at least 10 to 40 times higher for fiber reinforced concrete than for plain concrete. The increase in toughness of fiber concrete has proved that the fiber addition has an important role to bending resistance and ductility of concrete.

PROBLEM AND SCOPE OF DISSCUSSION

There are some limitations in current techniques of toughness characterization. It is important to pay attention in implementing the methods of flexural toughness evaluation of fiber reinforced concrete. This paper wants to review, compare, and discuss about some flexural toughness of fiber reinforced concrete evaluation methods such as ACI Committee 544 (ACI, 1978a), ASTM C 1018 (Trottier and Banthia,1994), CMOD (Balaguru and Shah, 1992), and also ASTM C 1399 (Banthia and Dubey, 1999, 2000), based on some relevant references and previous researches.

BASIC CONCEPT OF FLEXURAL TOUGHNESS

The main idea to add fibers to concrete is to improve the energy-absorbing capacity of the matrix, which can be evaluated by determining the area under the stress strain curve or by the load-deflection behavior. Balaguru and Shah (1992) emphazised that in the case of bending, the area under the load-deflection curve is used to estimate the energy-absorbing capacity or *toughness* of the material. By increasing toughness, there will be increasing of performance under fatigue, impact, and impulse loading. The toughness mechanism provides ductility.

It was also noted by Trottier and Banthia (1994) that the real advantage of adding fibers is that, after matrix cracking, fibers bridge the cracks and restrain them from widening. This process will help the integrity of material and improve the load-carrying capacity beyond cracking. Fibers hold the cracked matrix together and the continued deformation can occur if only a further input of energy exist that manifests itself as the long-descending branch of the load-deflection curve. This property of fiber reinforced concrete is referred as *toughness*.

The toughness index is used to indicate the ability of concrete elements to undergo larger deformations before failure. However, many factors can affect in the load-deflection performance and evaluation toughness, such as: fiber type, fiber geometry, fiber volume fraction, matrix composition, specimen size, loading configuration, loading rate, deflection-measuring accuracy, the type of control, and the stiffness of the machine compared that of the specimens.

METHODS OF FLEXURAL TOUGHNESS EVALUATION

ACI Committee 544 on Fiber Reinforced Concrete

Toughness calculation method (ACI, 1978a) can be implemented by using load-deflection curve of a simply supported 4x4x14 in (100x100x350 mm) or 6x6x21 in (150x150x450 mm) beam loaded at third point loading with supports 12 or 18 in appart and a load located at 4 or 6 in (100 or 150 mm) from the support. As mentioned by ACI Committee 544 (ACI, 1978a). The toughness index *It* can be written as

$$\mathrm{I_t} = \frac{A_{fc}}{A_{pm}} \qquad (1)$$

where It = toughness index, A_{fc} = area under the load-deflection curve until load reaches zero for fiber composite, A_{pm} = area under the load-deflection curve until load reaches zero for plain matrix.

In equation (1), the energy absorbed by a fiber reinforced composite beam is normalized by dividing it by the energy absorbed by identical beam made of plain matrix. Compare the method with older version of calculation of toughness index by ACI Committee 544 (ACI, 1978a) that is written as

$$\mathrm{TI} = \frac{A_{0.075d}}{A_{fc}} \qquad (2)$$

where TI = toughness index, $A_{0.075d}$ = area under the load-deflection curve to 0.075 in center point deflection, A_{fc} = area under the load-deflection curve to first crack. The difference between equation (1) and (2) is illustrated in Figure 1.

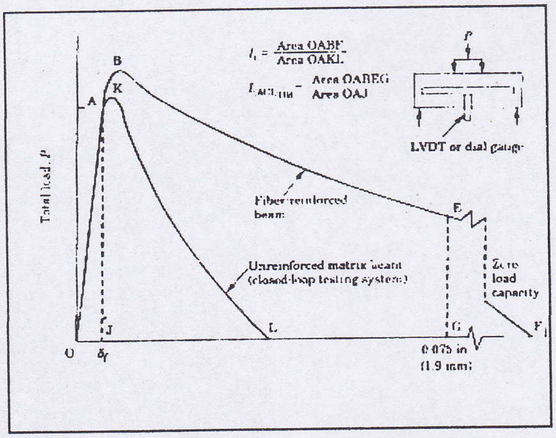

Figure 1. Measurement of Toughness and Toughness Index Definition by ACI (Balaguru and Shah, 1992)

The toughness index is dimensionless and is influenced by the amount, length, configuration, strength and ductility of the fibers, and other factors such as cement content, aggregate amounts, etc. However, this technique has practical limitations. It is difficult enough to cast identical plain concrete beams, besides in some cases, such as glass fiber reinforced cement composites, the load may not reach zero for very large deflection. Thus, a simpler testing procedure is needed, and ASTM C 1018 overcomes it.

ASTM C 1018

In ASTM C 1018 (Balaguru and Shah, 1992; Trottier and Banthia, 1994), the specimens used are fiber reinforced beams with preferred size of 4x4x14 in (100x100x350 mm). The equation of toughness index of ASTM C 1018 has in the denominator the area under the load-deflection curve up to the first crack, which is assumed to occur at the point where the load-deflection curve deviates from the initial linear portion. The numerator is specified as the area under the load-deflection curve up to certain specified deflection, specifically those of deflection of 3δ, 5.5 δ, and 10.5 δ or greater in case where large deflection prevails. The term δ is the deflection up to first crack. The three suggested indices of I_5, I_{10}, and I_{20} are defined by the following equations.

$$I_5 = \frac{A_{3\delta}}{A_\delta} \tag{3}$$

$$I_{10} = \frac{A_{5.5\delta}}{A_\delta} \tag{4}$$

$$I_{20} = \frac{A_{10.5\delta}}{A_\delta} \tag{5}$$

where A_δ = area under the load-deflection curve up to δ, $A_{3\delta}$ = area under the load-deflection curve up to 3δ, $A_{5.5\delta}$ = area under the load-deflection curve up to 5.5δ, $A_{10.5\delta}$ = area under the load-deflection curve up to 10.5δ. Figure 2 conveys the idea of those three indices above.

Or, in general terms, it can be written (Trottier and Banthia, 1994) as follows:

$$I_N = \frac{\int_0^{m\delta_c} P(\delta)d\delta}{\int_0^{\delta_c} P(\delta)d\delta} \tag{6}$$

where m = constant specifically those of deflection of 3δ, $5.5\,\delta$, and $10.5\,\delta$ or greater, δ_c = specimen deflection at the occurrence of first crack, δ = specimen deflection at midpoint, and $P(\delta)$ = function of δ.

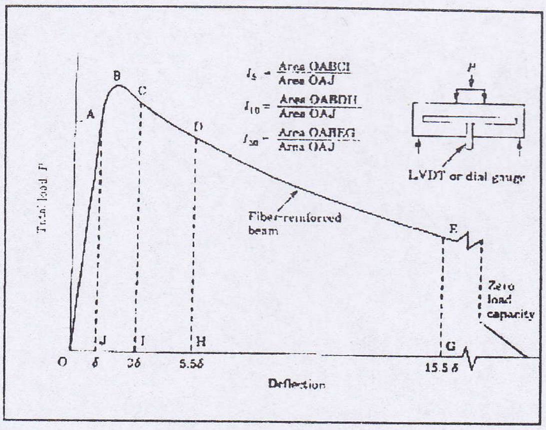

Figure 2. Measurement of Toughness and Toughness Index Definition by ASTM (Balaguru and Shah, 1992)

The deflection δ in the numerator of equations (3), (4), and (5) were chosen using elastic-perfectly plastic behavior as the datum, as shown by Figure 3, where the load-deflection curve is linearly elastic up to the first crack and perfectly plastic after cracking. For example, from Figure 3, the area under the curve up to 3δ would be $2.5P_c\delta$ and the area up to δ would be $0.5P_c\delta$. Therefore, the I_5 value will be 5. It is done similarly for I_{10} and I_{20}.

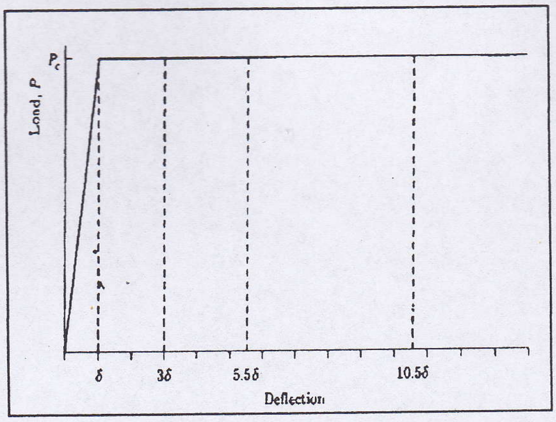

Figure 3. Load-Deflection Curve for Elastic-Perfectly Plastic Behaviour (Balaguru and Shah, 1992)

The strength remaining in the material is also characterized by means of residual strength factor R derived from toughness index [4]. According to ASTM C 1018, for example, the residual strength factor $R_{5,10}$ can be determined as $20(I_{10} - I_5)$, or in general terms by Trottier and Banthia (1994) is expressed as

$$R_{M,N} = C(I_N - I_M) \tag{7}$$

where constant C = $100/(N - M)$, chosen such that for an ideally elastoplastic material the residual strength factor assume a value equal to the stress at which the elastic-to-plastic transition takes place. Plain concrete, with its ideally brittle response, therefore, has residual factors equal to zero.

JSCE (Standard SF-4)

The method of toughness calculation by Japan Society of Civil Engineers (JSCE) (Balaguru and Shah, 1992), as shown by Figure 4, determines the energy required for deflecting beam by a specific amount. The absolute toughness T_{JCI} is defined as the area under the load-deflection curve to a deflection of span/150. For fiber length shorter than 40 mm, a beam cross section of 100x100 mm is recommended, and the 150x150 mm one is recommended for longer fibers. The recommended span lengths for smaller and larger beams are 300 and 450 mm. Another parameter, called the flexural toughness factor σ_b, a measure of the equivalent flexural strength is expressed by

$$\sigma_b = \frac{T_{JCI}.S}{\delta_{150}.w.d^2} \tag{8}$$

where S = beam span, w = beam width, d = beam depth, δ_{150} = $S/150$.

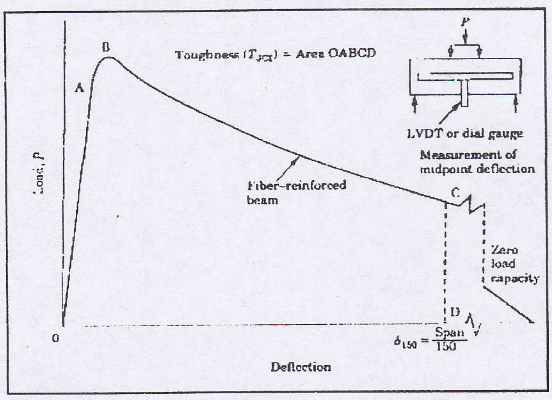

Figure 4. Measurement of Toughness and Toughness Index Definition by JSCE (Balaguru and Shah, 1992)

CMOD Control

In this method, the load can be applied using *crack mouth-opening displacement (CMOD)* control (Balaguru and Shah, 1992). As shown by Figure 5, a notch is cut at the midspan of the beam. The notch becomes the weakest section that let the crack initiation and growth occur at this location. Opening of the mouth of the crack is used as feedback to apply the load and provides the most stable postcrack response. As soon as the crack forms, the crack tends to open rapidly. Since crack opening is used as a control, the load is reduced by the servocontrol mechanism of the testing machine, avoiding the sudden failure.

The increase in crack width will represent the fracture energy of the beam and used as a measure of toughness of material. The crack mouth opening can be related to the rotation θ that occurs at the cracked section. If the small rotation assumed, rotation θ and crack mouth-opening displacement (CMOD) related by equation

$$\theta = \frac{CMOD}{(1-k)(d-a)+a} \quad (9)$$

where a = depth of the notch, d = depth of the beam, kd = depth of the neutral axes.

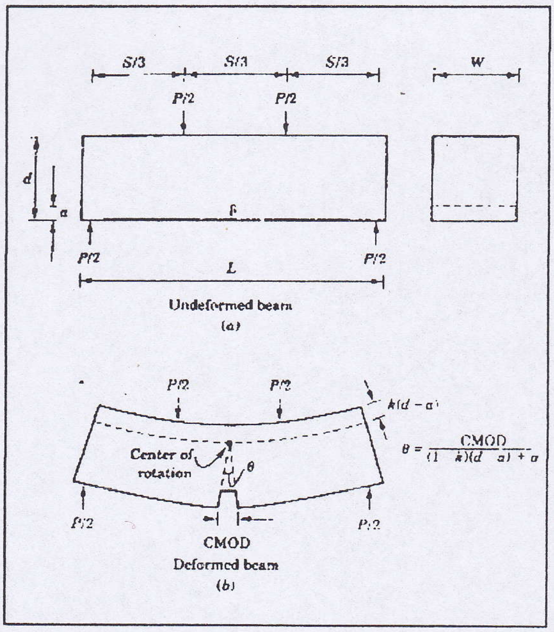

Figure 5. Schematic illustration of the Load-CMOD Approach for Toughness Measurement
(a) Undeformed Beam,
(b) Deformed Beam
(Balaguru and Shah, 1992)

Since the maximum bending moment M is $PS/6$ for beams loaded at midthird points with load P over a span of S, the energy absorbed $M\theta$ can be expressed as

$$\int_0^{\theta} M d\theta = \int_0^{CMOD} \frac{M}{(1-k)(d-a)+a} d(CMOD) \quad (10)$$

$$= \int_0^{CMOD} \frac{PS}{6[(1-k)(d-a)+a]} d(CMOD) \quad (11)$$

$$= \frac{S}{6[(1-k)(d-a)+a]} \int_0^{CMOD} P d(CMOD) \quad (12)$$

Equation (12) is used to compute the energy absorbed up to a chosen CMOD opening limit. The limit is similar to the limits used for deflection in toughness computations such as I_5, I_{10}, and I_{20}. In this case, the limit is crack width, as opposed to the deflection.

Load-CMOD plots can be used to identify the CMOD at first-crack. Toughness values can be non-dimensionalized using the energy required to create the first-crack. For example, the toughness at five times the first-crack CMOD can be obtained by using the equation

$$I_{CMOD5} = \frac{E_{CMOD5}}{E_{fc}} \quad (13)$$

where I_{CMOD5} = toughness at five times the first-crack CMOD, E_{CMOD5} = energy required for opening CMOD by five times the CMOD at first-crack, E_{fc} = energy required for the initiation of the crack

ASTM C1399

The fibers capability to improve toughness is their ability to transmit stresses across matrix cracks. It makes more sense to evaluate toughness by quantifiying the magnitude od stresses fibers which can transmit beyond matrix cracking. This property, often called postcracking strength (or the residual strength), is measured in stress units and is derived measure of toughness. The previous methods of quantifying toughness are using a flexural specimen where the instability can occur at the instant of peak load and causes the measurement meaningless (Banthia and Dubey, 1999, 2000). Answering the problem of instability, a new ASTM method (ASTM C 1399), have been accepted by obtaining the postcrack load-displacement response, called *Residual Strength Test Method (RSTM)*.

Banthia and Dubey (1999) has applied the RSTM that is explained as follow. A fiber reinforced concrete beam was tested under a third-point flexural load (following the ASTM C 78 method), with a 12 mm thick steel plate applied under the beam. The steel plate provides the support and absorbs the energy released by the machine at the peak load when the specimen develops a crack and the compliance of the specimen change suddenly. The plate will let the aggregate interlock to be maintained immediately after the peak load by limiting the extent of crack opening. A Japanese yoke placed around the specimen provides a measurement of the net displacement and the vertical elastic displacement of the loading fixture. The beam was loaded until a net vertical deflection between 0.25 and 0.50 mm reached, then the beam was unloaded and the steel plate was removed. In the next stage, the beam was reloaded until failure to obtain the residual load-deflection curve. The loads were noted when the beam reached midspan deflection at 0.5, 0.75, 1.0, and 1.25 mm. The residual strength (RS) values can be expressed as

$$RS = \frac{L}{bd^2}\left[\frac{P_{0.5} + P_{0.75} + P_{1.0} + P_{1.25}}{4}\right] \tag{14}$$

where $P_{0.5}$, $P_{0.75}$, $P_{1.0}$, and $P_{1.25}$ correspond to loads values at 0.5, 0.75, 1.0, and 1.25 mm beam midspan deflection, L = span, b = width of the beam, and d = depth of the beam. It should be noted that RS, which has the unit of stress, is not the true stress in the specimen, but some measure of an engineering stress (Banthia and Dubey, 1999).

Another property called the residual strength index (RSI) is also defined using the modulus of rupture (MOR) values as follow

$$RSI(\%) = \frac{RS}{MOR} \times 100 \tag{15}$$

DISSCUSSION

Some earlier researches have been conducted in measuring flexural toughness (Balaguru and Shah, 1992; Banthia and Dubey, 1999, 2000; Trottier and Banthia, 1994). Balaguru and Shah (1992) established the importance of fiber geometry and matrix strength on the toughness characteristics of steel fiber reinforced concrete. It should be noted that those researches were conducted applying straight, undeformed fibers, with high fiber volume fraction, which are rarely used in field application. The manufacture of steel fiber is being developed and still in progress with new inventions such as: production process, diversity of the fiber-shapes, and also the material constituents that is now blended of steel and synthetic fiber is introduced (www.nycon.com, 2003).

The methods of flexural toughness calculation mentioned above have been reviewed from the very first calculation until the latest, that there is always a more accurate and appropriate method of testing and evaluating procedure proposed by some investigators. In Figure 1, the calculation by ACI Comitttee 544 (ACI, 1978a) referred to zero load capacity (point F), and the deflection of 0.075 in shown by point G is determined by ACI Comitttee 544 (Balaguru and Shah, 1992). It can be understood that the two calculations will give different result of flexural toughness. In practical, ACI Committee calculation has difficulties in casting the plain beam and the fibrous beam in identical manner at the same time.

The limitation of flexural toughness calculation by ACI Comitttee was modified in a simpler procedure by ASTM C 1018 (Balaguru and Shah, 1992; Trottier and Banthia, 1994). The calculation is subjected to fibrous beams only, and uses the load-deflection curve with the deflection of first crack as valid reference. Determining the first crack point is very subjective, for example, it is very problematical to make sure where the point is in the region of non-linearity on curve. Trottier and Banthia (1994) noted that the deficiency of this method also includes determining the point of after peak curve region instability where the strain energy stored in the machine can be suddenly released. The method can fail to register the correct indices. The largest amount of energy dissipated cannot be observed by this method (Trottier and Banthia, 1994).

The JSCE method of flexural toughness calculation also has its limitations because of its specimen geometry dependency. The technique is also criticized for: (1) failing to distinguish between the pre-peak and the post-peak curves, and (2) using a smeared crack approach of the combined area under the curve to calculate the flexural toughness factor (Trottier and Banthia, 1994).

According to Khajuria, et. al. (1994) load-deflection responses using the CMOD (crack-mouth opening displacement) control will provide more stable response in the immediate post-peak region. Comparing the ordinary deflection control, at pre-crack region, both CMOD and ordinary deflection control show the same response. After the peak load, CMOD method shows a smooth transition from peak to post-peak reserve capacity. The result of [5] has shown that the strength of notched specimens under CMOD control is lower compared to unnocthed specimens under displacement control.

The implementation of ASTM C1399 by Banthia and Dubey (1999, 2000) shows that RSTM promises to provide results when the more accurate modified open-loop testing is conducted compared to those resulted by the closed-loop one. The RSTM imitates the closed-loop testing. Result of RS (*Residual Strength*) by closed-looped testing, however, stills the highest compared to open-loop testing and RSTM, but the advantage of RSTM is simpler procedure and application testing whether the closed-loop testing is difficult to run and time-consuming. The research has shown that RSTM has capability to distinguish the various fiber volume fractions of the same fiber type and also the various fiber types at a given volume fraction as well.

Among the methods of evaluating the flexural toughness mentioned above, the ASTM C 1018 and JSCE methods have become the simpler and more common methods compared to the CMOD and ASTM C 1399 methods. However, the ASTM C 1018 and JSCE methods still have its limitations. Answering the problem of ASTM C 1018 and JSCE methods deficiencies, a proposed technique to calculate flexural toughness was recommended by [4] and [2], called *Post-Crack Strength* (*PCS_m*) method, be illustrated in Figure 6.

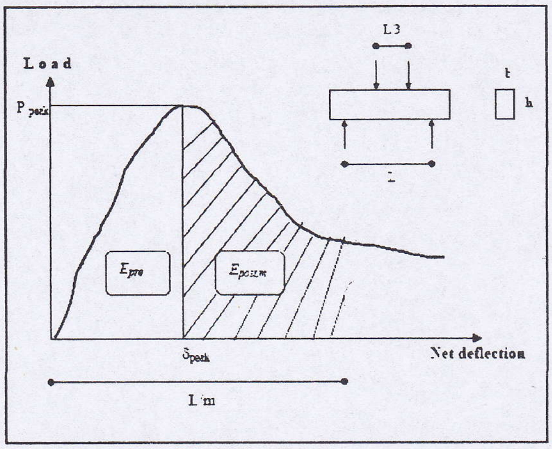

Figure 6. A Schematic Description of the Post-Crack Strength (PCS_m) Method (Dubey and Banthia, 1998)

The PCS_m method is similar to the JSCE flexural toughness factor, σ_b, but it considers the post-peak area only. The procedure of PCS_m method can be explained as follow:

a. Consider a given load-deflection curve as illustrated by Figure 6.
b. Locate the peak load; divide the curve into two regions (the area before the occurrence of the peak load and the area after the peak load). Note the value of load at the peak. Measure the area under the curve up to the peak load. The energy of this area denoted as E_{pre}.
c. Locate points on the curve in the post-peak region at specimen deflection equals to various fraction of the span, L/m, (for examples: L/m_1, L/m_2, L/m_3, etc.) where L = span, m = a number that is suggested between 150-3000. The value of m can be chosen depending on the application or even coincide with the Japanese value of 150. Depending on the equations (16) or (17) that is chosen to calculate post-crack strength, then measure : (1) the areas under the curve up to these deflections denoted as $E_{total,m}$, or (2) the areas under the curve after peak load up to these deflections denoted as $E_{post,m}$.
d. Calculate PCS_m in the post-peak region at the various deflections. The PCS_m at a deflection of L/m can be defined by

$$PCS_m = \frac{\left(E_{total,m} - E_{pre}\right)L}{\left(L/m - \delta_{peak}\right)b.h^2} \tag{16}$$

$$PCS_m = \frac{\left(E_{post,m}\right)L}{\left(L/m - \delta_{peak}\right)b.h^2} \tag{17}$$

where PCS_m = post-crack strength at deflection of L/m, $E_{total,m}$ = area under the load-deflection up to the deflections of L/m, E_{pre} = the area under the curve up to the peak load, $E_{post,m}$ = area under the load-deflection curve in the post-peak region deflection of L/m, L = beam span, b = beam width, h = beam depth, δ_{peak} = deflection at the peak-load, m = number that is suggested between 150-3000.

The post-crack strengths can be determined for any application of specific serviceability deflection. The slope of the obtained PCS_m vs. L/m curve qualitatively reflects the post-peak softening response of the composite. A steeper decrease of the slope will indicate a more brittle response. The slope will be zero for a linear-elastic perfectly plastic material. It should be noted that for high performance fiber reinforced concrete, brittleness of the matrix considerably affects the toughness behavior [2].

Table 1. Data and Result of Calculation - Beam A

BEAM A															
Δ	P		I_5	I_{10}	I_{20}	T_{JCI}	σ_b	$E_{post,m}$				PCS_m (MPa)			
mm	kN						MPa	L/3000	L/1500	L/600	L/150	L/3000	L/1500	L/600	L/150
0	0														
0.02	10	δ													
0.05	23														
0.06	18	3δ	8.4												
0.09	17														
0.1	17	L/3000						55				0.17			
0.11	17	5.5δ		18.7											
0.2	16	L/1500							71.5				0.11		
0.21	16	10.5δ			25.2										
0.3	15.5														
0.31	15.5														
0.4	15														
0.5	14.5	L/600								118				0.07	
0.6	14.3														
1.1	14.2														
1.3	13														
1.5	12														
2	9	L/150				253	0.038				183				0.027

Table 2. Data and Result of Calculation - Beam B

BEAM B															
Δ	P		I_5	I_{10}	I_{20}	T_{JCI}	σ_b	$E_{post,m}$				PCS_m (MPa)			
mm	kN						MPa	L/3000	L/1500	L/600	L/150	L/3000	L/1500	L/600	L/150
0	0														
0.02	6	δ													
0.05	7														
0.06	22	3δ	8												
0.09	18														
0.1	18	L/3000						38				0.11			
0.11	18	5.5δ		26.7											
0.2	17	L/1500							91.5				0.14		
0.21	17	10.5δ			38.2										
0.3	17.5														
0.31	17.5														
0.4	18														
0.5	18.5	L/600								179				0.11	
0.6	19														
1.1	18														
1.3	17														
1.5	16.8														
2	16.5	L/150				274	0.041				268				0.04

Table 3. Review of the Hypothetical Example Result

NO	METHOD	REVIEW
1	ASTM C 1018	At small deflection (such as I_5), this method fail to recognize the superior performance of beam B.
2	JSCE	This method cannot distinguish the two specimens performance at large deflections (L/150). This method is not able to recognize the superior performance of beam B at small deflections.
3	PCS_m	This method is able to recognize the superior performance of beam B at small deflections (L/3000, L/1500, L/600). This method is able to distinguish the performance of beam A and beam B at large deflection (L/150).

A very simple hypothetical example of flexural toughness of two 100x100x300 mm steel fiber reinforced concrete beam specimens is introduced in this paper. The objective of this example is making comparisons among ASTM C 1018 flexural toughness indices, JSCE absolute flexural toughness, and PCS_m method. From the load-deflection curve, the indices of I_5, I_{10}, I_{20}; flexural toughness factor, σ_b; and also the post-crack strength, PCS_m, at L/3000, L/1500, L/600, L/150 (see Table 1 and 2) and then plotted in the load-deflection curve as illustrated in Figure 6.

CONCLUSIONS

1. Among the methods of evaluating the flexural toughness that were reviewed, the ASTM C 1018 and JSCE methods are simpler and more common compared to the CMOD and ASTM C 1399 methods. However, the ASTM C 1018 and JSCE methods still have its limitations
2. The hypothetical example has shown that ASTM C 1018 and JSCE methods can't recognize the superior performance of beam B at small deflection. It was also noted that JSCE method can't distinguish the two beams performance at large displacement. In opposite, the PCS_m method can show the superior performance of beam B at small displacement, and also able to distinguish the two beams performance at large displacement
3. The *Post-Crack Strength* (*PCS_m*) method is promising because of its reliability due to specimen proper post-peak response of the load-deflection curve

ACKNOWLEDGMENT

The authors gratefully acknowledge Prof. Ir. Moh. Sahari Besari, MSc., PhD. for his great contributions of ideas, discussions, and intensive assistance to this paper which is expected to the growth of fiber reinforced concrete field.

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