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# The Cottrell Legacy: Metamorphosis of ICF into the World Academy of Structural Integrity 2011–2021 [1]

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**Abstract.** This paper is designed to address aspects of the immense contribution and enduring legacy of Sir Alan Cottrell FRS FREng FICF (1919–2012) – especially in the context of the creation and development of ICF – at the "ICF13 Memorial International Cottrell Symposium". One theme of this paper builds on the ICF0 paper of Cottrell in 1959, Cottrell's Opening Address at ICF2 in 1969 and Cottrell's ICF4 contribution "Fracture and Society" in 1977. A second theme of this paper is the BCS model of fracture and other models of fracture devised by Cottrell in the context of Cottrell's seminal 20th century contributions to the very creation of our disciplines of Structural Integrity and Materials Science: including archival research on the early work of Cottrell 1939–1941 on welding and cracking of low alloy steels at Birmingham. In particular, with the analytical BCS Model, Cottrell anticipated the numerical Cohesive Zone Models by at least two decades. This paper also addresses possible ways forward in this challenging 21st century for ICF-WASI following ICF13 in Beijing guided by the legacy of Cottrell's and Yokobori's ideas, inspiration and principles in establishing ICF during 1959–1969. At ICF13 the formal launch is arranged for the metamorphosis of ICF into "The World Academy of Structural Integrity". This is an ICF brand-development project explored at Sendai with Yokobori in 2010 and then initiated in 2011 at an ICF Interquadrennial Conference with ASTM in Anaheim, USA. This is much more than simply a name change but a comprehensive evolution in substance which like the original ten year creation process of ICF 1959–1969 is designed as a ten-year process 2011–2021. During the ICF13 Cottrell Forum in Beijing (as at the Sendai Interquadrennial in 2010) we seek full debate on the optimum ways forward for this metamorphosis.

Keywords: Alan Cottrell, plastic collapse, fracture propagation, size effects, cohesive crack model

## Nomenclature

| | |
|---|---|
| $a$ | crack length (cm) |
| $b$ | beam width (cm) |
| $K_I$ | stress-intensity factor (MN/m$^{3/2}$) |
| $K_{IC}$ | fracture toughness (MN/m$^{3/2}$) |
| $K_{IC}^f$ | fictitious fracture toughness (MN/m$^{3/2}$) |
| $\ell$ | beam span (cm) |

[1] This content was presented at the Professor A. Cottrell Memorial Minisymposium at ICF13, 2013, June, Beijing.

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$P$ external load (MN)
$P_f$ external load of brittle fracture (MN)
$P_p$ external load of plastic hinge formation (MN)
$s$ $K_{IC}/\sigma_y b^{1/2}$ = brittleness number
$t$ beam thickness (cm)
$\sigma^f$ nominal stress at failure (MN/m$^2$)
$\sigma_y$ yield strength (MN/m$^2$)

## 1. Introduction

This paper is designed as an international tribute to Alan Cottrell at ICF13 and especially as a tribute to Cottrell's contribution to the creation of ICF 1959–1969. Following the "ICF0" MIT Swampscott Conference "Fracture" in 1959 (at which Cottrell was a principal speaker) work began on the creation of ICF. In 1961 at MIT the "Interim International Fracture Conference Committee" was established with Takeo Yokobori (Japan) as Chairman and as Committee Members, Alan Cottrell (UK), Benjamin Averbach (USA), Jacques Friedel (France), Max Williams (USA), Alan Head (Australia), Peter Haasen (Germany), Norman Petch (UK), Serafim Nikolaievich Zhurkov (Russia). Thereafter ICF1 was organised by the Japanese Society for Strength and Fracture of Materials at Tohoku University, Sendai, Japan in 1965 with over 300 delegates from 18 countries.

It is quite interesting to note that two of the key eleven references in the MSc thesis of Alan Howard Cottrell (Birmingham, October 1940 "The Arc Welding of High Tensile Alloy Steels") were Honda and Sekito [1] and Honda and Nishiyama [2] both from Tohoku Imperial University, Sendai, Japan. Indeed these were key references in Cottrell's PhD thesis as "Bowen Metallurgical Scholar" supervised by Rollason and Hanson. So that the fracture research at Sendai and Tohoku University was familiar to Cottrell from at least 1939.

This is all found in the "Cottrell Archive" in the Metallurgy and Materials Library at Cambridge which is also interesting in regard to a sheaf of letters to Cottrell in 1948–1949 when a Lecturer in Metallurgy at Birmingham University from Walter Boas (CSIRO, Australia and formerly Berlin, Germany), M.B. Bever (MIT, USA), Egon Orowan (MIT USA), W. Hibbard (Yale, USA), R.F. Mehl (Carnegie, USA), Ulick Evans (Cambridge, England) indicating the strong thread of Cottrell's international connections still in his twenties as a young researcher, including with MIT.

ICF2 was held in 1969 in England with 480 delegates from 25 countries. A major driving force in this second conference at which ICF was founded was to be sure Alan Cottrell who presented the Opening Address with Roy Nichols as Quadrennial Conference Chairman. ICF3 was held in Germany in 1973 with some 500 delegates from 26 countries and ICF4 was held in Canada in 1977 with over 750 delegates from 38 countries.

An earlier paper (Taplin and Saxena) outlines the historical development of ICF and this paper along with the full ICF-WASI Archive is available on www.icfweb.org now formally launched. This includes the Proceedings from "ICF0", Swampscott 1959 through to ICF12, Ottawa 2009 and indeed ICF13, Beijing 2013 with plans forward regarding ICF14, Rhodes and ICF15, Vancouver, perhaps ICF16 Berlin 2025 we anticipate – plus various additional documents, papers and Interquadrennial Proceedings in a freely available internet library for the new "Academy".

This present paper builds on a Cottrell Forum paper at ICF4 "Fracture and Society" based on interviews with Cottrell in 1977 coupled to a series of interviews with current researchers who are legatees of

Cottrell's enduring inspiration. A second part of the present paper focuses on the BCS model and related models devised by Cottrell. A third part of this paper addresses the future of ICF as a World Academy.

Metallurgy is arguably the oldest scientific and engineering profession perhaps seven thousand years old and the metallurgists who helped create the Parthenon attest to this with lead coated iron clamps for the epistyles. Some would argue that metallurgy was mainly a qualitative "black-art" until being transformed by such as Cottrell and others in the 1940s and 1950s to a modern science through for example Cottrell's books on Structural Metallurgy and Dislocations. Cottrell built on the work of Taylor and Hume-Rothery and others in creating the modern quantitative science we know today but his many books attest to his enduring contribution.

Cottrell himself was brought-up in Birmingham in the inter-war years of industrial expansion and was trained in the older qualitative traditions based on optical metallography and one can discern this old (more art than science) tradition in Cottrell's MSc/PhD theses of over seventy years ago. In particular there are just two equations in Cottrell's PhD thesis on pages 38 and 83 which are simply stress calculation formulae. The thesis is based on simple tests and extensive optical metallography with an entirely qualitative approach consistent with the evolution of metallurgy as a discipline at that time.

Jim Charles was the first lecturer appointment Cottrell made at Cambridge as Goldsmiths' Professor in 1960 who one could deduce continued the black-art intuitive approach also researching archeometallurgy creating a wider perspective for the more modernistic new lecturers such as John Knott appointed by Cottrell at Cambridge. Knott worked with Cottrell from 1959 on his PhD on fracture of steels and therefrom until 1990 the Cottrell-inspired Knott Group was extremely active in our discipline. Indeed Knott is arguably Cottrell's foremost research student and co-worker who has made massive contributions (including as ICF President) and after over twenty years at Cambridge from 1990-present transferred his group back to Cottrell's alma mater Birmingham very successfully.

Arguably the most lasting contribution of Cottrell was through his years at Cambridge especially as Goldsmiths' Professor. Indeed a new "Cottrell Chair" is planned to be established at Cambridge in 2014 via especially contributions from former students of Cottrell. Probably the most prominent successor to Cottrell as Goldsmiths' Professor is Colin Humphreys who held this prestigious Chair from 1991–2008. Evidence suggests that the most significant research accomplishment (2000–2013) of Humphreys in the Cottrell tradition is on crack prevention/stress management in the manufacture of GaN for LED applications. Humphreys has also been Director of the Rolls-Royce Technology Centre at Cambridge since 1994 focussing on nickel-base superalloys with many outstanding achievements of this Rolls-Royce Centre. This is linked also to his appointment in the early 1990s of Julia King to replace John Knott when he left Cambridge for Birmingham and to be Deputy Director of the Rolls-Royce Centre, later joining Rolls-Royce as Director of Materials in Derby. King was a key appointment of Humphreys as Goldsmiths' Professor just as Knott was a key appointment of Cottrell himself when Goldsmiths' Professor. A key Cottrell Legacy is also the many world-class and very influential series of textbooks and programmes of Mike Ashby on Materials Design. In addition to ICF and the new World Academy the chief guardians ongoing of the Cottrell Legacy are Knott, Humphreys and Ashby and in a further paper we shall explore these legacy aspects of Cottrell.

There is an extensive oral interview of Cottrell in the archives of the British Library which covers his whole career anecdotally and since Cottrell's death there have been very many tributes and obituaries published including an extensive review by John Knott which is available now on the www.icfweb.org website. Accordingly there is no need to here delve in to the very many books and works by Cottrell, his great fount of ideas that inspired generations of researchers and transformed various realms of science and engineering. Our task is to examine the international inspirations and legacy of Cottrell especially in the discipline of our newly burgeoning World Academy of Structural Integrity and the contribution to Society. Documents from Trevor Churchman, Harold Paxton, Jacques Friedel and others have come to light via ICF and Ron Armstrong is assembling a parallel paper to our own to thereby create a debate in a Cottrell Forum at ICF13. So that this paper is simply one short introduction to this Forum which is additionally designed to address the further metamorphosis in comprehensive substance of the new "Academy" through ICF14 in Rhodes in June 2017 and to ICF15 in Vancouver in July 2021 as a ten year project.

Already noted is the new Academy Internet Library launched in Turin, Italy in August 2012. The Gold Medal prestigious awards in the names of the three most significant creators of ICF based on a micro–macro vision, Takeo Yokobori, Alan Cottrell and George Irwin were established at ICF12 in Ottawa in July 2009. Building on the original ICF Interquadrennial in Beijing in November 1983 we now have a comprehensive programme of several Interquadrennial Conferences each year. As well we now have a global network of MoU agreements with various societies and institutions. There are plans at ICF13 to establish a programme of "ICF-WASI Regional Directors" – perhaps as many as a dozen to create a proactive Academy programme regionally for the common good. Many other significant ideas have been mooted for the new Academy and all these should be explored for the beneficial development of our Academy here in Beijing.

## 2. BCS model

Due to the different physical dimensions of tensile strength [F] $[L]^{-2}$ and fracture toughness [F] $[L]^{-3/2}$, scale effects are always present in the usual fracture testing of common engineering materials. This means that, for the usual size scale of the laboratory specimens, the ultimate strength collapse or the plastic collapse at the ligament tends to anticipate and obscure the brittle crack propagation.

Such a competition between collapses of a different nature can be described through a cohesive crack tip modelling. The ductile-brittle transition when the specimen size increases is captured by the well-known BCS-model [3,4]. The substantial assumption is the transition from "stress vs. strain" to "stress vs. displacement" constitutive law when the ultimate tensile strength is locally achieved.

The experimental results [5] obtained from size-scaled polymeric three point bending specimens (width $= 1/2, 1, 2, 4, 8, 12$ cm) are predicted theoretically. For each value of width, five different relative crack depths are considered: $a/b = 0.1, 0.2, 0.3, 0.4, 0.5$. Except for the larger specimens, the fracture process was stable and very ductile, but no necking near the crack was noticed. The plastic zone in front of the crack tip presented a strip-shape. A simple plastic collapse at the ligament occurred for small size scales ($b = 1/2, 1, 2$ cm), whereas the transition from plastic collapse to brittle fracture is reproduced by the cohesive crack model satisfactorily up to the asymptotic situation of very large specimens, for which LEFM is totally valid.

The experimental material is polypropylene Moplen® D 60 P, originally provided in slabs $100 \times 200 \times 4$ cm. The main properties of the material are:

Melt flow rate: 0.46 g/10′ (ASTM, D 1238-73)
Young's modulus: 1400 MN/m$^2$ (ASTM, D 790-71)
Yield strength: 33 MN/m$^2$ (ASTM, D 638-77)
Density: 0.912 g/cm$^3$ (ASTM, D 1505-68).

Three point bend specimens have been obtained from these slabs. Specimens maintained the original thickness of slab (4 cm), but their width $b$ and length $\ell$ have been varied so that the constant ratio $\ell/b = 4$

always resulted. The following values of width $b$ have been chosen: 0.5, 1, 2, 4, 8, 12 cm, which nearly constitute a geometric progression. The bending tests have been performed by a displacement controlled Instron machine. Thus the loading velocity was controlled so that all the utilized sizes were subjected to the same strain rate, by applying the formula:

$$\dot{\varepsilon} = \frac{6V_0 b}{l^2},$$

where: $V_0$ = velocity of the point of load application. Such a formula is strictly applicable to un-notched specimens. The strain rate was $\dot{\varepsilon} \simeq 0.001\ \mathrm{s}^{-1}$. In the case of polymers it is important to work with constant strain rate, to avoid effects on yield strength and fracture mechanics parameters.

For each value $b$ of the specimen width, five different relative crack depths have been utilized: $a/b = 0.1, 0.2, 0.3, 0.4, 0.5$.

The tests were carried out at 23°C.

The competition between plastic collapse at the ligament and brittle crack propagation can be easily proved by considering the ASTM formula for the three point bending test evaluation of fracture toughness (Fig. 1):

$$K_{\mathrm{I}} = \frac{Pl}{tb^{3/2}} f\left(\frac{a}{b}\right), \tag{1}$$

with:

$$f\left(\frac{a}{b}\right) = 2.9\left(\frac{a}{b}\right)^{1/2} - 4.6\left(\frac{a}{b}\right)^{3/2} + 21.8\left(\frac{a}{b}\right)^{5/2} - 37.6\left(\frac{a}{b}\right)^{7/2} + 38.7\left(\frac{a}{b}\right)^{9/2}.$$

At the crack propagation condition Eq. (1) becomes:

$$K_{\mathrm{IC}} = \frac{P_{\mathrm{f}} l}{tb^{3/2}} f\left(\frac{a}{b}\right), \tag{2}$$

where $P_{\mathrm{f}}$ is the external load of brittle fracture. If both members of Eq. (2) are divided by $\sigma_{\mathrm{y}} b^{1/2}$ we obtain:

$$\frac{K_{\mathrm{IC}}}{\sigma_{\mathrm{y}} b^{1/2}} = s = \frac{P_{\mathrm{f}} l}{\sigma_{\mathrm{y}} t b^2} f\left(\frac{a}{b}\right), \tag{3}$$

where $s$ is a dimensionless number able to describe the brittleness of the specimen [6,7]. Rearranging of Eq. (3) gives:

$$\frac{P_{\mathrm{f}} l}{\sigma_{\mathrm{y}} t b^2} = \frac{s}{f(a/b)}. \tag{4}$$

On the other hand, it is possible to consider the non-dimensional load of plastic hinge formation at the ligament:

$$\frac{P_{\mathrm{p}} l}{\sigma_{\mathrm{y}} t b^2} = \left(1 - \frac{a}{b}\right)^2. \tag{5}$$

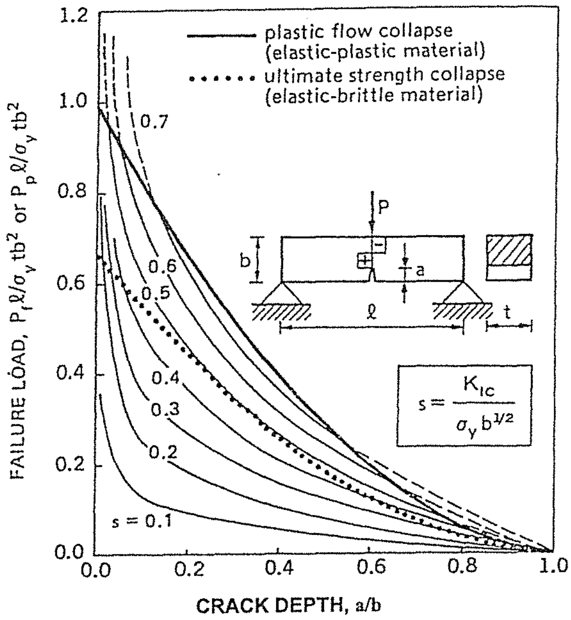


Fig. 1. Interaction between plastic collapse and brittle crack propagation.

Equations (4) and (5) are plotted in Fig. 1 as functions of the crack depth $a/b$. While the former produces a family of curves by varying the brittleness number $s$, the latter is represented by a unique curve. It is easy to realize that plastic collapse precedes crack propagation for each crack depth when the brittleness number is higher than the critical value $s_0 = 0.75$. For lower s numbers plastic collapse anticipates crack propagation only for crack depths external to a certain interval. This means that real fracture phenomena occur only for sufficiently low fracture toughness, high yield strengths and/or large structural sizes. It does not matter the single values of $K_{IC}$, $\sigma_y$ and $b$. What is important is only their functions.

Recalling Eqs (4) and (5), we can obtain the ratio between fictitious and real fracture toughness, which is equal to the ratio between load of plastic collapse, $P_p$, and load of crack propagation, $P_f$, when $P_p < P_f$, and equal to unity when $P_p > P_f$:

$$\frac{K_{IC}^{f}}{K_{IC}} = \frac{P_p}{P_f} = \frac{1}{s}\left(1 - \frac{a}{b}\right)^2 f\left(\frac{a}{b}\right) \quad \text{for } P_p < P_f, \tag{6a}$$

$$\frac{K_{IC}^{f}}{K_{IC}} = 1 \quad \text{for } P_p > P_f. \tag{6b}$$

Combining the definition of brittleness number, Eqs (3), (6a) and (6b), it results:

$$\frac{K_{IC}^{f}}{\sigma_y b^{1/2}} = \left(1 - \frac{a}{b}\right)^2 f\left(\frac{a}{b}\right) \quad \text{for } P_p < P_f, \tag{7a}$$

$$\frac{K_{IC}^{f}}{\sigma_y b^{1/2}} = s \quad \text{for } P_p > P_f. \tag{7b}$$

Equation (7a) is represented in Fig. 2 as a bell-shaped curve vanishing for $a/b = 0$ and $a/b = 1$. It presents a maximum for that value of crack depth for which the fracture curve $s = s_0$ is tangent to

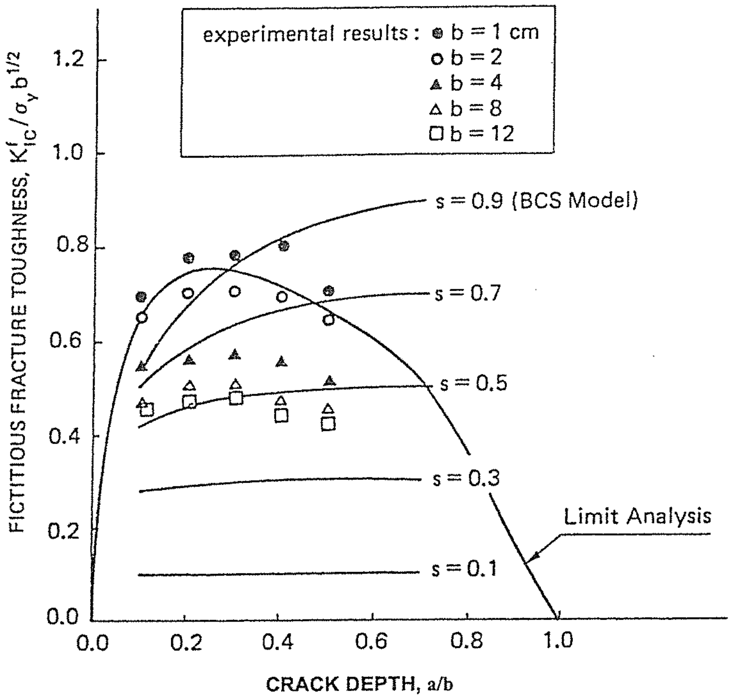


Fig. 2. Fictitious fracture toughness vs. crack depth.

the plastic flow curve in Fig. 1. More precisely, for $s > s_0$ Eq. (7a) is valid for each crack depth $a/b$, whereas for $s < s_0$ Eq. (7a) is valid for external crack depths and Eq. (7b) for central crack depths.

Equation (7a) is represented also in Fig. 3 by varying the specimen width $b$. The dark shaded area is where the curves $a/b = 0.1$ to $a/b = 0.5$ are concentrated. It is a very narrow strip, specially for not too large sizes $b$. When $s > s_0$, the parabola (7a) is replaced by the horizontal straight line $K^f_{IC} = K_{IC}$. The experimental points present a course which is only initially similar to that of Eq. (7a). This means that, only for small specimens ($b = 0.5/1.0/2.0$ cm) the collapse can be perfectly described by a plastic flow at the ligament. By increasing the size scale a transition occurs from plastic flow towards a true LEFM collapse. For $b = 12$ cm, however, the latter has not been reached yet, since the experimental points are still ascending. It is difficult to predict the true value of fracture toughness exactly. On the other hand, if the experimental work went on with larger specimens, it would be possible to standardize an extrapolation technique with a smaller number of specimens.

An attempt is done to describe the ductile-brittle transition through the BCS-cohesive crack model (1, 2). The following expression for the fictitious fracture toughness is assumed:

$$K^f_{IC} = \sigma^f(\pi a)^{1/2} F(a/b), \tag{8}$$

where $\sigma^f$ is the nominal stress at failure and $F$ is the shape-function in the Tada–Paris–Irwin notation (6). If it is recalled the equivalence:

$$F\left(\frac{a}{b}\right) = \frac{2f(a/b)}{3(\pi a/b)^{1/2}}, \tag{9}$$

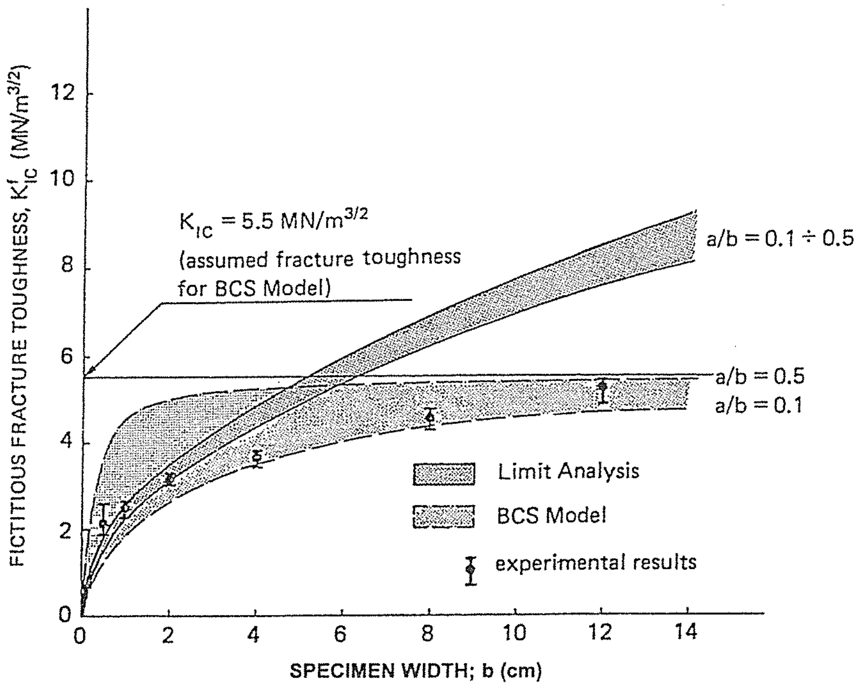


Fig. 3. Fictitious fracture toughness vs. specimen width.

between Tada–Paris–Irwin function and ASTM function, the BCS fracture toughness:

$$K_{\mathrm{IC}}^{\mathrm{f}} = (\pi a)^{1/2} F\left(\frac{a}{b}\right) \frac{2}{\pi} \sigma_{\mathrm{y}} \cos^{-1}\left\{\exp - \left[\frac{\pi K_{\mathrm{IC}}^2}{8\sigma_{\mathrm{y}}^2 a F^2(a/b)}\right]\right\}, \tag{10}$$

is transformed as follows:

$$\frac{K_{\mathrm{IC}}^{\mathrm{f}}}{\sigma_{\mathrm{y}} b^{1/2}} = \frac{4}{3\pi} f\left(\frac{a}{b}\right) \cos^{-1}\left\{\exp - \left[\frac{9\pi^2 s^2}{32 f^2(a/b)}\right]\right\}. \tag{11}$$

Equation (11) is plotted in Fig. 2 as a function of crack depth $a/b$ and varying the brittleness number $s$. The experimental points are on the limit analysis curve for $b = 1$ and 2 cm, whereas they fall below for larger specimens.

Equation (11) is represented also in Fig. 3. According to the BCS model, it is necessary to assume a true $K_{\mathrm{IC}}$ value to be inserted into Eq. (11). The value $K_{\mathrm{IC}} = 5.5$ MN/m$^{3/2}$ is that which best-fits the experimental results. The family of curves $a/b = 0.1$ to $a/b = 0.5$ is more spread for small than for large sizes in this case. The opposite occurs for the limit analysis prediction. It is very clear from Fig. 3 that a simple plastic collapse at the ligament occurred for small size scales ($b = 0.5/1.0/2.0$ cm), whereas the transition from plastic collapse to brittle fracture is captured by the BCS model satisfactorily, specially for shallow cracks ($b = 4.0/8.0$ cm). The asymptotic situation of very large specimens is described by LEFM consistently.

With the analytical BCS Model, Alan Cottrell and co-workers anticipated the numerical Cohesive Zone Models by at least two decades (7).

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