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An alternative method for determining tensile properties of engineered cementitious composites

Benny Suryanto[a,*], Blair Cockburn[a], Han Ay Lie[b], W. John McCarter[a]

[a]Heriot-Watt University, Edinburgh EH14 4AS, Scotland, United Kingdom
[b]Diponegoro University, Semarang 5027, Indonesia

Abstract

The framework of a practical test method that can be used to provide indirect assessment of the tensile properties of ECC is presented. Particular emphasis is placed on providing the underlying concept, modelling strategy and constitutive relations underpinning the proposed framework. An analysis case study, examining the effect of tensile stress-strain profiles on the flexural response of an ECC beam, is presented to demonstrate the capability of the modelling approach. The results of further parametric analysis are also provided to establish equations that can be used for determining equivalent tensile properties of ECC based on a given set of flexural test data. A web portal is provided as a simple tool for practitioners and researchers involved in mix development and quality control testing.
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Keywords: ECC; practical test; tensile properties; quality control; virtual laboratory; website

1. Introduction

An Engineered Cementitious Composite (ECC) is a fiber reinforced cement-based composite which possesses ultra-ductile tensile properties, typically a few hundred times larger than those possessed by concrete with no and regular fiber reinforcement [1–3]. The material's high tensile strain capacity is attributed to its ability to form closely-spaced fine cracks when subjected to tension, allowing it to deform plastically like a metal – a response which is known as a strain hardening [4]. This is in contrast to the post-cracking response of ordinary concrete which

* Corresponding author. Tel.: +44-131-451-3817; fax: +44-131-451-4617
E-mail address: b.suryanto@hw.ac.uk

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is characterized by a brittle, strain softening response. Apart from its high ductility, ECC is known for its crack control ability, with crack widths typically less than 100μm during the strain hardening [5]. It is these two ECC features that have attracted widespread interest from the engineering community.

In the United Kingdom, where this research is conducted, ECC has yet to be used in civil engineering applications, with the work still being at a research and development stage (see, for example, [6–9]). In order to promote the use of ECC in the construction industry, this work seeks to develop a simple test procedure that can be used for quality control testing in large volume applications. While the uniaxial tensile test has been the primary method used for ascertaining the tensile stress-strain properties of ECC and provides results which are easy to analyze, the test is often difficult to perform to an acceptable quality and thus can be impractical for use in normal construction practice. It is for this reason that a simpler test method is developed in this work. Although the proposed method can stand alone, it is not the intention of the authors to replace the standard tensile test, but rather to use it alongside the existing test method which should be used for validating the results periodically.

2. Heriot-Watt University (HWU) Method

A flowchart detailing the work undertaken to develop the HWU method is presented in Fig. 1, with the dashed lines highlighting the scope of this paper. The proposed method is similar in many respects to the University of Michigan (UM) method [10,11] on the basis that it only requires the peak load and the corresponding point-load deflection to be measured from a test. Similar to the UM method, the proposed method also does not require the use of special devices to take strain readings; rather, this can be determined using predefined equations, which can also be used to determine tensile strength. The proposed method is distinct from the UM method in that it offers an improved representation of the effect of micro-cracking on beam curvature and deflection profiles, making it more closely aligned with the principles of mechanics (Fig. 2). Another important aspect of the HWU method, when compared to the UM method, lies in the use of refined stress-strain relations which are used consistently throughout the calculation process. Fig. 3(a) presents the test setup used to derive equations used in the proposed method.

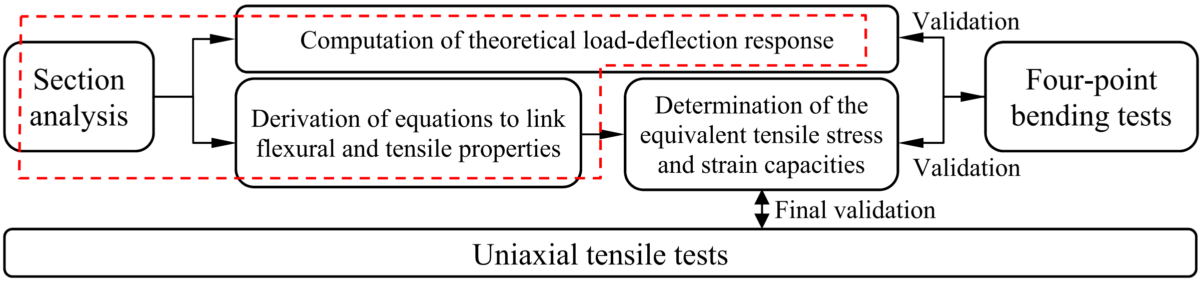


Fig. 1. Framework for the development of the HWU method.

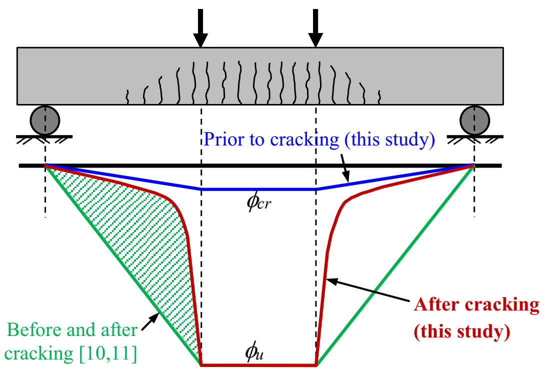
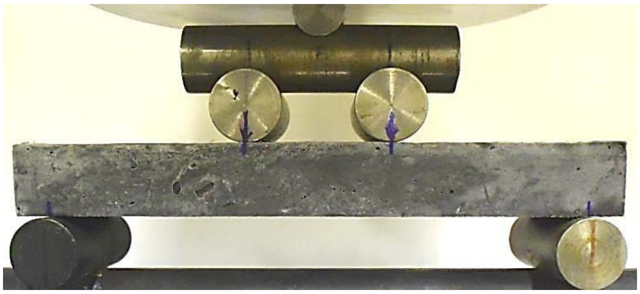
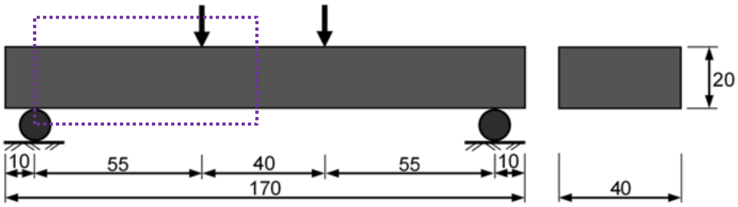


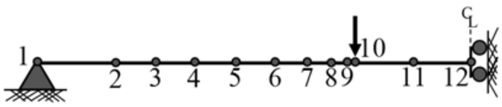
Fig. 2. Comparison of the assumed curvature profile in HWU and UM methods, with the hatched area highlighting the difference.



(a)



(b)



(c)

Fig. 3. (a) Proposed test setup; (b) schematic and dimensions of test sample (in mm); and (c) structural model representation of half of the test sample (marked with a dotted rectangle in (b)).

3. Analytical Model

3.1. Modelling

Fig. 4 presents the analytical model used to predict the full-response of the beam, with only half of the beam being modeled due to the symmetry in load and support conditions. A total of 12 nodal points (or, accordingly, 11 elements) were used to represent half of the beam. On this individual point, it was assumed that the beam cross-section comprises a stack of ECC layers having the same width b and depth dh. It was also assumed that plane sections remain plane, provided that the shear span-of-depth ratio of the test specimen used in the HWU method is large enough (a/d = 2.75; see Fig. 3a). It is on this basis that the calculation employs a linear strain profile.

Section analysis was performed at multiple locations along the beam (Points 2–12) and at each point, the depth of the beam was divided to 1000 layers, with the strain and stress values on each layer assumed to be uniform (see Fig. 4). Although significantly smaller number of layers could actually be used without significantly affecting the accuracy of the analysis, it was decided to use such a large number in order to obtain smooth strain and stress profiles and guarantee the highest levels of accuracy. The stress and strain on each layer were then individually analyzed using predefined stress and strain relations shown in Fig. 4, which are based on the work by [12–14]. On each section, iterative calculations were carried out to obtain the longitudinal strain and stress profiles whilst satisfying, respectively, the compatibility and equilibrium requirements. Two tensile stress profiles were used to form the tensile stress-strain response: a constant stress distribution ($\alpha = 1.0$) and a bilinear stress distribution ($\alpha < 1.0$). To suit the typical tensile properties of the ECC mix developed at Heriot-Watt [6], α for the bilinear stress model was taken to be 0.7.

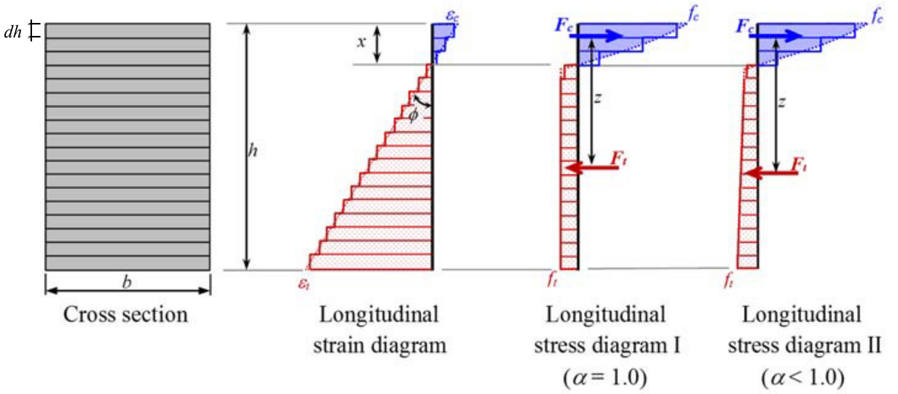


Fig. 4. ECC sample discretized into layers and the corresponding strain and stress profiles across the depth.

3.2. Constitutive models

The constitutive relations proposed by Suryanto *et al* [12,13] were used. The curve describing the monotonic response in compression is based on the elasto-plastic fracture model for concrete [15]:

$$f_c = \omega_c K_0 E_0 (\varepsilon - \varepsilon_p) \tag{1}$$

where fracture parameter K_0, initial stiffness E_0 and plastic strain ε_p are defined as

$$K_0 = \exp\left(-0.73\frac{\varepsilon}{\varepsilon_c'}\left(1-\exp\left(-1.25\frac{\varepsilon}{\varepsilon_c'}\right)\right)\right) \tag{2}$$

$$E_0 = 2\frac{f_c'}{\varepsilon_c'} \tag{3}$$

$$\varepsilon_p = \beta\left(\frac{\varepsilon}{\varepsilon_c'} - \frac{20}{7}\left(1-\exp\left(-0.35\frac{\varepsilon}{\varepsilon_c'}\right)\right)\right) \tag{4}$$

where f_c' is the ECC compressive strength, K_o is a fracture parameter, ε_c is the plastic strain, ε_c' is the strain at the peak compressive strength and β is the strain-rate factor. The strength reduction factor due to transverse cracking, ω_c, is taken as 1.0. The base response in tension is assumed to be bilinear, with the first part describing the elastic response of the ECC and the second part describing the strain-hardening response, as given by

$$f_t = \omega_t E_e \varepsilon_t \qquad 0 < \varepsilon_t < \varepsilon_{tcr} \tag{5}$$

$$f_t = \omega_t E_{sh} \varepsilon_t \qquad \varepsilon_{t,cr} < \varepsilon_t < \varepsilon_{tu} \tag{6}$$

where E_e is the initial elastic modulus of the ECC (approximately 20GPa) [7], ε_t is the tensile strain, ε_{tcr} is the tensile strain at first cracking, ε_{tu} is the tensile strain capacity, ω_t is a reduction factor to account for transverse cracking.

Given that the principal stress direction remained constant throughout the testing, it was anticipated that there was no transverse cracking forming and hence the strength reduction factor, ω_t, was taken as 1.0. Failure was defined as the moment when the tensile strain at the utmost bottom layer reached the tensile strain capacity, ε_{tu}, and no post-peak response was considered. Section analyses at multiple locations along the beam were carried out using Microsoft Excel.

4. Analysis Results and Discussion

To demonstrate the capability of the calculation framework described in Section 3, two series of analysis were undertaken to simulate the response of an ECC sample with sample dimensions and test set-up following the schematic presented in Fig. 3(a). In total, eighteen analysis cases were performed (nine for each tensile stress model). In each analysis case, different tensile strain values were used at the utmost bottom layer, including 0.03%, 0.075%, 0.15%, 0.30%, 0.45%, 0.75%, 1.50%, 2.25% and 3.0%. The mechanical properties of the ECC were taken as f_c' = 30 MPa, f_{tu} = 4 MPa and ε_{tu} = 3.0%. In the bilinear stress analysis case, f_{tcr} was taken as 2.8 MPa, whereas E_{sh} was taken as 40.2 MPa throughout.

Fig. 5 presents the computed load versus point-load deflection of the ECC beam using the assumed two tensile models. It is evident that the post-cracking tensile stress-strain profiles had a profound effect on the nonlinear part of the load versus deflection curves, which represents the post-cracking response of the beam. The elastic-plastic model (α = 1.0) produces a much sharper load-deflection response after first cracking, a flatter post-cracking response during the intermediate to final parts of the curve and a slight increase in load capacity. The sharp increase in response along with lower deflection values could be attributed to the value of the stress at first cracking, f_{tcr} which is taken equal to that at ultimate state, f_{tu}. The same theory applies to the approximately flat-top response with increasing deflection, as well as to the marginal increase in load capacity. It is interesting to note that the assumed tensile stress-strain profiles also affect the deflection at the peak load. This can be attributed to the difference in the crack distribution at the underside of the two beams. The larger deflection at peak load shown by the bilinear stress distribution indicates that the cracks that form at the bottom of the beam are more uniform. The evidence for this can be seen from Fig. 6, which shows that the elastic-plastic stress distribution (α = 1.0) produces a much more drastic curvature profile as it reaches the center span than that of the bilinear distribution (α = 0.7). In addition, regardless the tensile models used, it is evident that the computed curvature profile is highly nonlinear which is in sharp contrast to the linear profile assumed by [10,11] (see Fig. 2). The assumption in linear curvature distribution may affect the accuracy of the deflection prediction, and hence the equivalent tensile strength and tensile strain capacity.

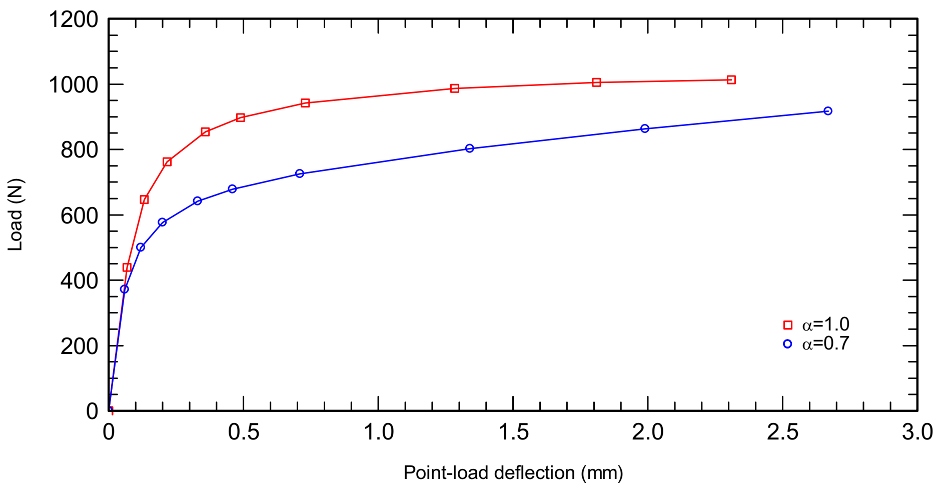


Fig. 5. Predicted load versus load-point deflection responses of an ECC sample presented in Fig. 3(a) and 3(b). The mechanical properties of the ECC are taken to be f_c' = 30 MPa, f_{tu} = 4 MPa and ε_{tu} = 3%.

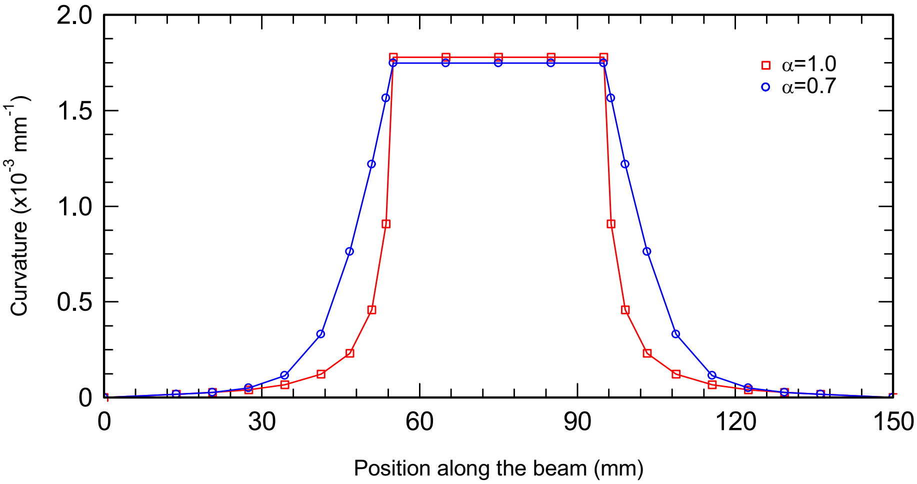


Fig. 6. Predicted curvature profiles for bilinear ($\alpha = 0.7$) and elastic-plastic ($\alpha = 1.0$) tensile models.

The analytical framework was then used to undertake a parametric study to investigate the influence of a wide range of possible ECC mechanical properties. In total, 56 analysis cases were run for the two tensile stress-strain models considering a variety of compressive and tensile strength and tensile strain values. The parameters considered in the parametric study include compressive strength (30, 40 and 50 MPa), tensile strength (3.5, 4 and 5MPa) and tensile strain capacity (0.5, 1, 3 and 4%). It is interesting to note from the results of the parametric analysis that although the beam exhibits a highly nonlinear response, the tensile strain capacity, ε_{tu} exhibits an almost linear relationship with point-load deflection, δ_u at peak load and is, to a lesser extent, affected by compressive strength, f_c'. Based on this finding, the following empirical equations are proposed to determine the equivalent tensile strain capacity, ε_{tu} from a given point-load deflection and compressive strength

$$\varepsilon_{tu} = \frac{f_c'}{10}(0.028\delta_u + 0.017) + 1.43\delta_u - 0.29 \qquad \text{for elastic-plastic model } (\alpha = 1.0) \qquad (7)$$

$$\varepsilon_{tu} = \frac{f_c'}{10}(0.015\delta_u + 0.021) + 1.21\delta_u - 0.21 \qquad \text{for bilinear model } (\alpha = 0.7) \qquad (8)$$

To determine the equivalent tensile strength, further derivations were performed using the analytical procedure described in Section 3. To summarise the findings from the derivations, the tensile strength can be found for either tensile model by

$$\left[\left(-0.5\frac{(h-x)}{E\varepsilon_{tu}}\right)f_{tu}^2 + (h-x)f_{tu}\right]b(0.52h) = 27.5P \qquad \text{for elastic-plastic model } (\alpha = 1.0) \qquad (9)$$

$$\left[\left(\frac{\alpha+1}{2}\right)(h-x)\right]0.54bhf_{tu} + \left[0.5\frac{\alpha^2(h-x)}{E\varepsilon_{tu}} - \left(\frac{\alpha+1}{2}\right)\left[\frac{\alpha}{E\varepsilon_{tu}}(h-x)\right]\right]0.54bhf_{tu}^2 = 27.5P$$

$$\text{for bilinear model } (\alpha = 0.7) \qquad (10)$$

where x is the neutral axis depth, E is the Young's Modulus and P is the applied load. For more details on the derivations of Equations 7–10, the reader should refer to [16].

To aid with the use of Equations 7–10, which are tedious to solve by hand, an Excel spreadsheet was developed along with a user-friendly website '*ECC Calc*', built using HTML and CSS scripting languages. The JavaScript library was used to generate the equations and perform intermediate calculations according to the user's input. The first generation of the website is now available at http://dkwebsolutions.net/ECC-Calc/. The webpage was designed in such a way that the browser can perform calculations quickly even through a dial-up connection, allowing access from around the world including countries with limited internet access. Fig. 7 shows the main interface of the website. A user can simply populate the form shown on the right and click the 'Calculate' button to perform the calculation. The results will be then shown automatically as presented in Fig. 8. The website can also be downloaded to a smartphone for use in a laboratory setting. New features will be incorporated in the near future to give users an option to visualize the calculated results.

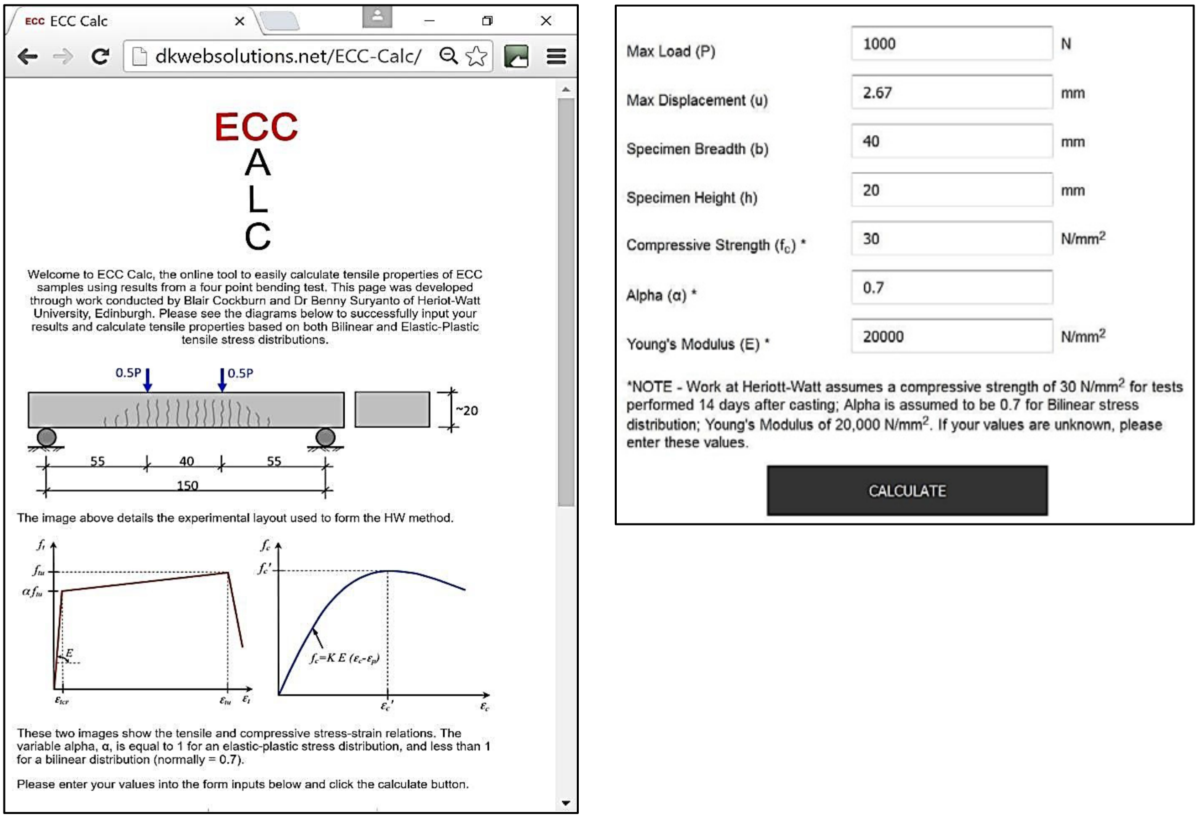


Fig. 7. Screenshot of the *ECC Calc*'s main interface with boxes shown in the right for user input (available at http://dkwebsolutions.net/ECC-Calc/).

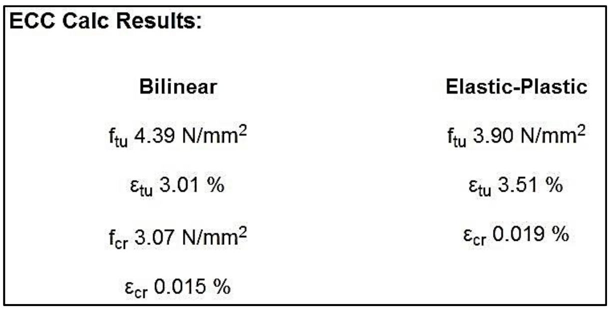


Fig. 8. Screenshot of the calculated output provided by *ECC Calc*.

4. Concluding summary

The framework of a practical test method for characterizing the tensile properties of ECC is presented. The proposed framework comprises three primary parts: (i) a test method, which is based on the well-known four-point bending test; (ii) an analytical framework, which is based on the beam theory and incorporates nonlinear constitutive relations of ECC, and; (iii) a web portal, which can be accessed either on-site or in the laboratory via a computer or smartphone. This framework is called the Heriot-Watt University (HWU) test platform. In this paper, the proposed framework was used to simulate the response of an ECC sample under four-point bending and to develop relationships between flexural tests and tensile properties. It has been shown that the assumed tensile stress-strain response has a significant influence on the load capacity, deflection capacity, computed tensile strength and tensile strain capacity. Choosing an appropriate tensile stress-strain profile is shown to be essential to achieve the necessary level of accuracy with regard to the computed tensile strain and stress capacities. Future work will be directed towards extending the modelling platform for use with existing test methods. The first generation of a web portal is introduced to provide a practical tool for ascertaining the tensile properties of ECC.

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