Cement & Concrete Composites 58 (2015) 95–104

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Derivation of a simplified stress–crack width law for Fiber Reinforced Concrete through a revised round panel test

Fausto Minelli *, Giovanni Plizzari

DICATAM – Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy

ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 27 December 2014
Accepted 4 January 2015
Available online 7 February 2015

Keywords:
Fracture toughness
Fiber Reinforced Concrete
Round panel
Constitutive law
Test scatter
Kinematic model

ABSTRACT

The Round Determinate Panel (RDP), according to ASTM, was found to be a reliable, consistent and repeatable test method for the measurement of the energy absorption in Fiber Reinforced Concrete (FRC) composites. A smaller panel was proposed and experimentally investigated by the authors in previous scientific contributions.

An analytical approach is herein reported toward the definition of a simplified stress–crack width law for FRC, determined from tests on small panels according to the requirements of Model Code 2010 for tension softening materials. To this aim, the measurement of the three crack widths was implemented in the test procedure and, in addition, a kinematic approach was proposed to predict the crack width of panels.

1. Introduction

FRC is a structural material nowadays integrated in several international building codes, including the recent Model Code 2010 (referred to as MC2010 in the following) [1,2]. An innovative aspect of the MC2010 concerns the definition of the FRC performance according to its mechanical properties and not based on the fiber geometry, material and content. The simplest test for the material characterization is the beam test, prescribed by several national and international standards, usually based either on a three [3,4] or four point bending schemes [5]. Early experiences with the low volume fractions of fibers that are nowadays mostly used in practice ($V_f < 0.3$–1.0%), evidence that the characteristic values determined from beam tests are remarkably smaller than the mean values because of the high scatter in beam test results. The latter is not related to the material itself but is mainly due to the small fracture areas (areas of cross sections at notch, ranging from 160 to 190 cm^2) linked by a little number of fibers. Such a scatter becomes particularly high when low contents (25–50 kg/m^3) of macro steel fibers (length ranging between 30 and 60 mm) are used [6].

The large scatter is a significant drawback both for verifying the material conformity and for the calculation of the design parameters that, according to MC2010, depend on the residual strengths determined from material characterization tests.

As an example, the post-cracking design law that correlates the residual post-cracking strengths to the crack width is given in Fig. 1 [1,2]. MC2010, according to [3], defines the residual strengths $f_{R,j}$ that are effective parameters that any engineer might use for the design of FRC structures. Based on $f_{R,j}$, MC2010 introduces the following two design parameters:

$$f_{\mathrm{Fts}} = 0.45 \cdot f_{R,1} \tag{1}$$

$$f_{\mathrm{Ftu}} = f_{\mathrm{Fts}} - \frac{w_u}{\mathrm{CMOD}_3}(f_{\mathrm{Fts}} - 0.5 f_{R,3} + 0.2 f_{R,1}) \geqslant 0 \tag{2}$$

where

- $\mathrm{CMOD}_3 = 2.5$ mm;
- w_u is the maximum crack opening accepted in structural design; its value depends on the ductility and it is basically significant for design purposes; generally $w_u = \mathrm{CMOD}_3 = 2.5$ mm, as assumed in the following.

It is evident that a higher experimental scatter results in smaller values of f_{Fts} and f_{Ftu}, and this is only due, in the case of beam tests, to a not proper experimental geometry for the material characterization.

This is why, as accepted by MC2010, other types of tests might be considered provided that correlation factors are available and proven. As an alternative, a widely available test is the Round Determinate Panel (RDP) test, published by ASTM [7] and standardized for the measurement of energy absorption of Fiber

* Corresponding author.

http://dx.doi.org/10.1016/j.cemconcomp.2015.01.005
0958-9465/

Reinforced Concrete (FRC) with special emphasis on sprayed concrete for tunnel linings. It is a statically determinate test, with round shape slab having a diameter (ϕ) of 800 mm and a thickness (t) of 75 mm, supported in three points at 120°. The standard test is rather straightforward and only requires load and displacement measurement. The specimen weight is 91 kg.

This test is not used, so far, for the determination of the mechanical properties of FRC (i.e. toughness indexes and residual post-cracking strengths), which are traditionally derived from beam tests.

It is commonly accepted that FRCs with a low volume fraction of fibers ($V_f < 0.5\%$) are particularly suitable for structures with a high degree of redundancy where stress redistribution may occur [8]. Because of this redistribution, large fracture areas are involved (with a high number of fibers working at cracks) and, consequently, structural behavior is mainly governed by the mean value of the material properties. Furthermore, because of the large fracture areas, the scatter of experimental results from structural tests is remarkably lower than that obtained from beam tests.

In order to get hold of a more realistic value of the scatter in FRC material tests, standard tests should be carried out on specimens with larger fracture areas; this suggests the use of larger beams or different specimen geometries like slabs, where a stress redistribution may also occur.

This brought the authors to extend the potential of the ASTM RDP toward the FRC mechanical characterization. However, handling and placing a classical round panel is quite difficult due to the large size and, consequently, to the high weight (unless adopting a rolling steel form, as stated by ASTM C 1550-10 [7]). In addition, standard servo-controlled loading machines may not fit with the geometry of the RDP, which is excessively large for many of them. The need of having a specimen that is easier to handle brought Minelli and Plizzari [9] to come up with a proposal of a Small Round Determinate Panel (SRDP) having:

- a diameter of 600 mm (effective diameter of 550 mm);
- a depth of 60 mm;
- a weight of 40 kg.

The diameter over the depth ratio is 10, whereas in the classical RDP is 10.67; in both the cases, a sufficient specimen slenderness can be observed and it is higher than that in all beam tests abovementioned. As a consequence, panel tests provides a better representation of the bending behavior of materials.

Moreover, measurement of the three crack openings could be also implemented in the test, as the crack pattern is repeatable

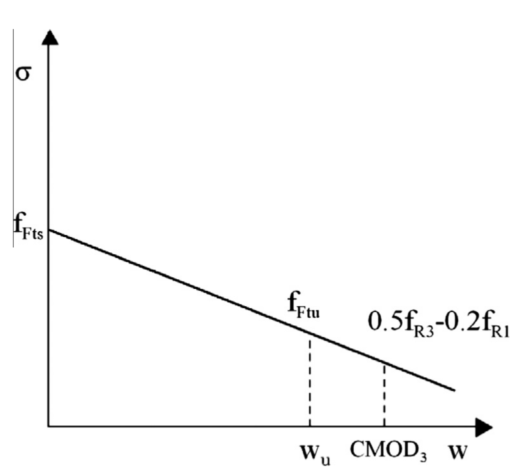

Fig. 1. Typical σ–w simplified uni-axial constitutive law according to MC2010.

and predictable; therefore, the post-cracking material properties can be adequately determined. In addition, handling and placing such a specimen is easier as compared to the classical round panel, since its weight is only 40 kg, if compared to the 91 kg of the ASTM panel. Finally, standard servo-controlled loading machines generally fit with the geometry of the small panel, allowing for a crack-controlled tests with a close-loop system, which is suitable for standard tests on FRC specimens.

Based on a broad experimental campaign [9] on more than 50 SRDPs, it was found that the proposed smaller specimen, besides the abovementioned advantages:

- does not affect the low scatter of results from the classical ASTM RDP, which is consistently lower than in classical beam tests, and
- produces results that are consistent, reliable and repeatable.

Therefore, the SRDP test could be considered as a complete test for the characterization of FRC (identification of constitutive laws). Fig. 2 reports typical load–crack width curves from beam tests [3] and load–displacement curves from SRDP tests, for two FRC materials containing either 20 or 30 kg/m^3 of steel fibers. The two plots clearly evidence the remarkable lower scatter of the experimental curves from panels [9] and, therefore, the potential of the proposed test.

The present investigation focuses on the applicability of the SRDP tests for deriving a simplified σ–w law for FRC strain-softening materials as required by MC2010 [1,2]. Numerical elastic analyses and a kinematic approach will be both utilized to this aim; in particular, the latter will be evaluated in terms of quality of prediction of cracking and compared against the experimental results.

The simplified σ–w law derived is based on the flexural strengths f_{Rj} as defined in [3] and also required by MC2010 [1,2]. Unlike other similar studies [10,11]], this research not only intends to compare SRDP to other tests, but especially aims at establishing SRDP as a comprehensive and reliable test for the FRC characterization, with special focus on those structural applications in which FRC is provided in small thickness, i.e. sprayed concrete or tunnel lining applications [12], structural plaster overlays for retrofitting [13] and thin webbed elements.

2. Analytical study

2.1. Overview and scope of the analytical study

The SRDP proposed in [9] will be in the following considered for the derivation of FRC fracture properties (i.e. post-cracking constitutive law and residual post-cracking strengths) once a suitable testing and analytical procedure is established.

The methodology, already adopted in many FRC standards for beam tests [3,5,14], is based on the determination of a stress–crack width curve, in which:

- The stress can be derived from theory of elasticity, i.e. the flexural stress is just the moment over the section modulus of the notched or critical un-notched section (after cracking, it can be considered as a conventional stress).
- The crack width is the Crack Tip Opening Displacement (CTOD) or the Crack Mouth Opening Displacement (CMOD), as measured in specific points of the specimen.

It should be observed that the conventional stress is a rather rough simplification but it allows for the definition of handy post-cracking strengths or toughness indexes without any non-linear analysis, which could be hardly performed by practitioners.