Validation of an Experimental Methodology for Measuring Concrete Fracture Energy in Existing Structures

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Abstract. Numerical modeling is often used to assess the load-carrying capacity of existing structures, especially for complex structural systems such as bridges. These numerical models are always sensitive to certain parameters, such as the mechanical properties of the materials. In the case of concrete structures, the tensile strength and fracture energy of concrete have demonstrated great influence in the numerical evaluation of deformations and capacity. However, for existing structures, the fracture energy value is mainly estimated using empirical formulae based on the concrete compressive strength, as there is no methodology to evaluate it experimentally. This issue leads to uncertainty regarding the obtained values and subsequently influences the results of finite element models (FEM) and capacity prediction. With the aim of reducing this uncertainty, an experimental methodology for the evaluation of the fracture energy in existing structures is validated in this paper. First, uniaxial tensile loading tests were carried out on notched standard cylinders and drilled cores specimens cast under laboratory conditions. Then, crack opening versus load curves and fracture energy values were compared to those obtained from three-point bending tests in notched beams and Finite Element Modeling. The results showed that the proposed methodology can be a potential method to estimate the fracture energy of existing structures, and the notch depth have an influence on the fracture energy value obtained.

Keywords: Existing structures · fracture energy · tensile strength · experimental test · numerical modeling

1 Introduction and Background

Structures' behavior is mainly governed by the mechanical properties of their materials. Therefore, it is important to accurately assess those properties to have an accurate prediction of capacity and performance of any given structure. This is particularly important for the case of concrete, which is known for being a heterogeneous material, i.e., its mechanical properties are spatially dependent. In addition, the concrete mechanical properties may change considerably throughout time, depending on climate factors such as cold temperatures, and the loading cycles provoked by vehicles or snow, among other

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issues. Thus, when assessing the capacity of existing concrete structures, such as concrete bridges, it is important to update its main material parameters trough the extraction of material samples.

Fracture Energy (G_f) is among the more critical properties of concrete. Nowadays, there is a diverse number of methods for quantifying it. The direct method to obtain the tensile softening curve of concrete is the stable uniaxial tensile test [1, 2]; however, because of its difficulty and some other drawbacks pointed out in literature [3, 4], normally indirect procedures are applied instead.

The three-point bending (3PBT) test is one of the most used indirect methods to determine the fracture energy of concrete in practice [5], which is based on the cohesive models of [6], further developed by [7, 8]. It has been stated in the literature, that this method may produce considerable experimental error [1, 9], and therefore several studies have been focused on testing the effect of different parameters when performing 3PBT, to reduce the error. As an example, [10] studied the effect of size, crack length and post-peak softening based on experimental data provided by [11].

The four-point bending test (4PBT) can be also found and its configuration is very similar to the three-point bending test. The difference between 3PBT and 4PBT is that for 4PBT the force applied on the upper surface is divided into 2 points, and distributed equally on both sides of the notch, instead of applying all the load on the notch in the center of the beam. A positive fact about this method is that the fracture energy can be obtained directly from the load-displacement curve with the fracture energy being the area below the crack mouth opening displacement (CMOD) curve.

In addition to the 3PBT and 4PBT, other methods were proposed such as the Compact Tension Test (CTT) presented in [12]. Itis mainly used to evaluate the parameters and characteristics of concrete or asphalt pavements, or various binder materials. Its major advantage is its high versatility since it can be applied both to laboratory samples and to specimens extracted directly from existing structures. A less conventional method is the one proposed in [13], in which instead of placing the notch under the tested beam, places it on the top surface. The beam is supported by 4 springs which, in turn, are aligned with the rollers.

In [14], a method called wedge splitting test (WST) is introduced. The method is based on the results proposed by [15]. This new method overcomes the disadvantages of the 3PBT and CTT methods. The uniaxial tensile test (UTT) was initially used over cylindrical samples without a notch [16–18], and along the years, this method has received some changes such as the specimen size and shape.

Among the more recently developed methods, it can be highlighted the cohesive crack model, previously called the fictitious crack model. Relevant information on this method can be found in [19]. Also, the new concept of local Fracture Energy applying 3PBT, proposed in [20], in which the crack is modeled as an "elastically equivalent notch", where the effective crack length is equal to the depth. This method presents the advantage of using less samples of different shapes, notch-to-depth ratios, or sizes.

Snozzi, L. et al. [21] presented an innovative computational model with the purpose of investigating the mechanical response of concrete specimens or samples tested to dynamic compressive and tensile loading. This new model combines the interface debonding and the frictional contact, and it consists in modeling concrete using a meso-mechanical approach. Snozzi et al. [21] concluded that the rise in strength is directly linked to a higher Fracture Energy dissipation. More information regarding these methodologies is given in [22].

It can be noticed that no recent efforts have been performed to assess the fracture energy of existing structures, therefore, the method known as Uniaxial Tension Test performed in [23] is studied in this paper with the objective of improving the understanding of its accuracy and applicability for existing structures cases.

The purpose of this study is to use Finite Element Modeling (FEM) as a tool for investigating the importance of the sample geometrical properties, i.e., notch depth and core length, on the calculation of the concrete fracture energy (G_f). Also, uniaxial tests and 3PBT are carried out in the laboratory for a case study, to compare and calibrate the data obtained through FEM.

2 Methodology

This section contains the details of the experimental work carried out to determine the fracture energy of a new concrete trough bridge, as well as the details of the FEM used to investigate the importance of the notch depth and sample length when performing direct uniaxial tests aim to calculate G_f values.

2.1 Experimental Work

A new trough concrete bridge was cast at Luleå University of Technology (LTU) in northern Sweden to be tested under different load conditions. During the casting of the bridge, different concrete samples were collected to obtain its mechanical properties, such as the compressive (f_c) and tensile (f_{ct}) strengths, the modulus of elasticity (E_c) and the fracture of energy (G_f). Table 1 displays the different samples collected and the test to be performed. The focus in this study is the determination of G_f, therefore, tests concerning other than G_f values are not explain here. A concrete slab was also cast using the same concrete of the bridge and cores were extracted to perform UTT.

Table 1. Type of concrete samples collected, and the type of test performed.

Type of sample	Type of Test
Rectangular beams	3PBT
Cubes	Compression
Cylinders	Compression, UTT, and Modulus of elasticity
Slab cores	UTT, compression

The UTT was carried out with a modification, which consists of creating a notch at L/2 of the sample, i.e., the notch is at the same distance from the top and the bottom of the sample (see Fig. 1). This strategy was previously implemented in [24], where the fracture energy for an existing structure under analysis, and it was pointed out that for existing structures samples of beams are difficult to be taken due to the geometry.

In this study the test was applied for both cast cylinders and cores extracted from the cast slab. The objective of extracting the cores from the slab is to simulate the case of an existing structure and compare with those cast as cylinders. A total of 10 samples were tested, and their respective dimensions are specified in Table 2 in Sect. 3 presented together with the results. The tensile strength of the core samples is calculated using the following equation:

$$\sigma_t = T_{max}/A \tag{1}$$

where T_{max} is the failure load and A is the cross-section area of the core sample at the notch.

For the test, it was used a displacement rate of 0.05 μm/s, and once the load reached 0.5 kN, this displacement rate was increased to double, i.e., to 0.1 μm/s to decrease the time of the test. The test setup is shown in Fig. 1.

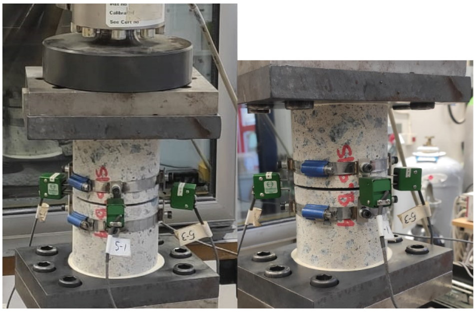

Fig. 1. Uniaxial tensile test layout for a concrete core.

The beams were prepared, creating a notch at mid-span, as required by the 3PBT, with a notch depth (a) of approximately 0.33 times the width of the beam. The notch is instrumented to monitor the crack opening, and the beam is simple supported with the point load placed on the top surface at mid-span. The dimensions of the tested beams are presented in Table 4 in Sect. 3, together with the results.

The value of the fracture energy is obtained by determining area under the stress-crack width curve. Three of the extracted cores from the slab were tested to compression, so the value of G_f can be obtained from the empirical formulation given by the fib Model Code 2010 [25] (see Eq. 2), which depends on the value of the concrete compressive strength f_c (in MPa). The value obtained from the empirical equation is compared with those obtained from the UTT.

$$G_f = 73 \cdot f_c^{0.18} \tag{2}$$

2.2 Finite Element Modeling

The tests presented in the previous section were simulated in the Finite Element (FE) software ATENA Science v.5.9, with the purpose of verifying the accuracy of the tests, and to perform a sensitive analysis. The models were developed using 3D hexahedra elements (or brick elements), with 8 nodes, and a mesh size between 10 and 8 mm for the cylinder and 0.3 for the notched section (see Fig. 2). The bottom surface of the sample is restricted in the vertical (y) and horizontal direction (x), and the upper surface is restricted in the horizontal direction (z). The load is applied on the top surface as a displacement in the positive direction of y (traction).

The implemented fracture model for concrete is based on the classical orthotropic smeared crack formulation and crack band model. It employs Rankine failure criterion, exponential softening, and fixed crack model. The tensile behavior of concrete is defined using the softening exponential curve proposed by Hordijk & Reinhardt [26]. In compression, the Menétrey-Willam model is adopted, which considers the plasticity of concrete in the multi-axial state.

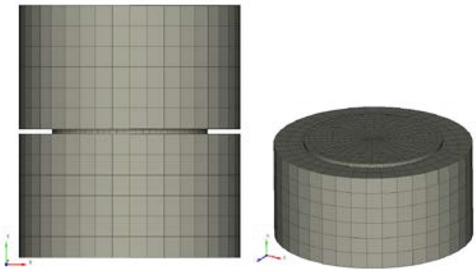

Fig. 2. Illustration of the FEM of a notched concrete core with the mesh configuration.

Initially, before the performing the experiments a first group of cylinders with length $L = 200$ mm and different notch depths (80, 70, 60, and 50 mm) were modelled, with the objective of analyzing the importance of the notch depth. The concrete properties used for this group of cylinders corresponds to the design concrete of the through bridge (f_c = 45 MPa) and with values f_{ct} = 2.66 MPa and G_f = 145 (N/m) calculated according to the fib Model Code 2010 [25]. The G_f is obtained for each model by measuring the area of the stress-crack width curve after the maximum tensile force (F_{max}).

A second group of models were developed to represent the cores used in the UTT (listed in Table 2.) which can be summarized into 4 types of cylinders: lengths 150 mm and 100 mm with notch diameter 70 mm, and lengths 170 and 130 with notch diameters 60 mm (see Table 5), and the concrete properties used for the 4 models correspond to the ones obtained through the UTT and compression tests performed.

3 Results and Discussion

The results obtained from the uniaxial test are shown in Table 2, and the obtained curves for each one of the tested cores are presented in Fig. 3. Table 3 contains the compression results for three different cores, and the respective $G_{f,emp}$ calculated from Eq. 2, and the results obtained from the 3PBT for each one of the beams are listed in Table 4.

Table 2. Dimensions and results from the uniaxial test.

Core	L_c(mm)	Φ(mm)	Φ_D(mm)	F_{max}(kN)	σ_{max}(MPa)	$G_{f,exp}$(N/m)
Cylinder 1	100	100	70	Sample failed before completing the test		
Cylinder 2	150	100	70	12.3	3.2	131.9
Core 1	170.3	97.1	60.1	8.9	3.1	112.7
Core 2	164.0	97.1	60.1	9.0	3.2	148.7
Core 3	131.8	97.4	60.1	Glue failure		
Core 4	134.1	97.5	60.0	7.6	2.7	151.6
Core 5	133.3	97.5	60.2	Glue failure		
Core 6	133.9	97.5	60.1	8.8	3.1	117.5
Core 7	136.2	97.3	60.1	7.7	2.7	118.1
Core 8	124.9	97.0	60.2	8.5	3.0	100.8

where L_c is the longitude of the core/cylinder, Φ and Φ_D are the original and notched diameter, respectively, and A_{notch} is the cross-sectional area of the notched part of the sample.

Table 3. Compression test results obtained from the slab cores.

Core	F_{max}(kN)	f_c(MPa)	$G_{f,emp}$(N/m)
Core 9	425	57.5	151.4
Core 10	435	58	151.6
Core 11	385	51.3	148.3
		Mean	150.4

where s is the span length, i.e., space between supports, L_b is the total length of the beam, b and d are the width and height, respectively, and a is the notch depth.

The values of G_f obtained from the uniaxial tests and the 3PBT are similar, and since the samples were collected from the same concrete batch, this indicates that the tests provided an accurate G_f value. The values of G_f from the uniaxial tests have a coefficient of variation COV = 15.04%, from which a percentage of this variation belongs to the

Table 4. Dimensions and results of the 3PBT.

Beam	S (mm)	L_b(mm)	b (mm)	d (mm)	a (mm)	F_{max}(kN)	$G_{f,exp}$(N/m)
1	400	600	78.3	128.56	42.85	4.9	119.3
2	375	480	75	125	41.67	5.4	118.1
3	400	600	77.50	127.50	42.50	4.5	120.9

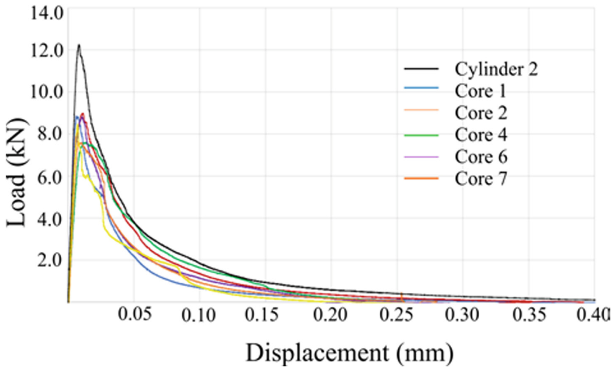

Fig. 3. Load-Deflection variation curve obtained from the proposed methodology.

fact that the samples were tested with different notch depths and core lengths. During the tests, some of the samples reached a 'glue failure', i.e., the failure was presented on the faces in contact with the epoxy used to glue the load plates. This failure was obtained on cores with higher length, which highlights the importance of establishing an adequate notch depth related to a determine L.

The $G_{f,emp}$ calculated through Eq. 2 and using the f_c values of the compressive tests are higher than the ones obtained from UTT and 3PBT. If taking the mean value displayed in Table 3 as the theoretical value of $G_{f,theo} = 150.4$ (N/m), the average error of the UTT and 3PBT is 16% and 21%, respectively.

Figure 4 presents the load-displacement curves obtained through the FEM. Figure 4a. Contains the curves for the cylinders with $L_c = 200$ and different notch depths, from which it is possible to observe that the various notches provide significant different curves, with a great variation of F_{max}. Bigger notch depths (smaller A_{notch}) result in smaller F_{max}. Figure 4b. Displays the curves for the main geometries of the tested cores, and it is possible to see that for the same notch diameter, the curves are similar, despite the different lengths, which can also be observed in Fig. 3 where the curves are similar for the cores with notch diameter 60 mm, and the only core with different curve is for the cylinder with notch diameter 70 mm.

Table 5 shows the values of F_{max}, f_{ct} and G_f calculated from the curve in Fig. 4, for the different models. The models that obtained a better accuracy, i.e., the ones with G_f calculated with the curve closer to the one assigned in the model, were L200_DN60 and

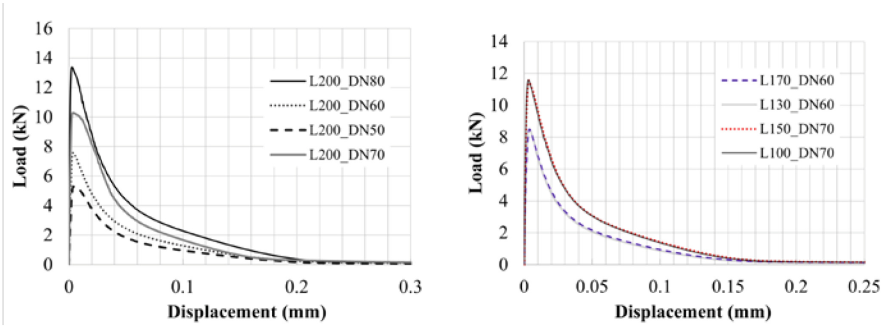

Fig. 4. Load-displacement curves for a. the different notch depths and constant L = 200 and b. the cores tested in laboratory.

Table 5. Dimension and results from the FEM analyses.

Model name	L_c(mm)	Φ_D(mm)	F_{max}(kN)	f_{ct}(MPa)	G_f (N/m)
L200_DN80	200	80	13.4	2.7	139.0
L200_DN70		70	10.3	2.7	141.7
L200_DN60		60	7.6	2.7	144.6
L200_DN50		50	5.3	2.7	155.1
				COV	4.8%
L170_DN60	170	60	8.5	3.0	120.7
L150_DN70	150	70	11.5	3.0	125.7
L130_DN60	130	60	8.5	3.0	117.0
L100_DN70	100	70	11.6	3.0	125.2
				COV	3.36%

L150_DN70, and both have a notch depth-length ratio of 0.1, which indicates that this can be an optimal value for this type of test.

The FEM and the tests showed an agreement since the G_f values and curves obtained for both methodologies were close. For instance, if comparing FEM and experimental curves for the cores with notch diameter 60 mm, a F_{max} around 8.5 and displacement at F_{max} equal to 0.01 mm were reached, and for the cores with notch diameter 70 mm a F_{max} around 12 and displacement at F_{max} equal to 0.01 mm.

4 Conclusions and Future Work

Experimental and numerical evaluations of concrete samples have been carried out to determine the fracture energy G_f. Based on the experimental and FEM results the following conclusions can be drawn:

- The length of the cores and cylinders have an influence on the success of the experiments. For longer cores, a deeper notch needed to be used to avoid their failure at the surfaces in contact with the glue.
- The FEM simulations showed that the notch depth has a great influence on the behavior of the sample; however, when obtaining the G_f value, as the notch area is considered, the different is not significant, variations of 4.8% and 3.3% for the two groups of models.
- This method seems to be a good option for determining the value of G_f for existing structure; however, to improve and obtain more standard notch depth-length ratios, more tests can need to be performed on samples from existing bridges.

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