The Small Punch Test as a Tool for Basic Structural Integrity Assessments

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Abstract. Many of the procedures used in structural integrity assessments have a hierarchical scheme which allows analysis to be performed according to different levels or options as a function of the information available on the material. Thus, basic level analyses are performed using material data obtained from relatively simple tests, making it unnecessary to carry out further analysis if the results are acceptable. One of the tests which, thanks to its specific characteristics, could be used in these levels is the Small Punch Test since it is a simple, fast and inexpensive test and allows samples of in-service components to be tested because of the reduced dimensions of Small Punch specimens.

This work, taking as a reference the recently developed FITNET procedure, analyses the suitability of the application of Small Punch tests at basic levels. All material parameters required in the structural integrity assessments of FITNET standard options have been reviewed and, in each case, a methodology for obtaining them from Small Punch tests is proposed. Finally a validation example of the application of this approach is included.

Introduction

One of the main inputs of structural integrity assessment is the one constituted by the group of mechanical properties of the analysed component [1]. In those cases of assessment of in-service structures or failure analysis this aspect can be especially critical since these properties are not always known and usually there is not enough material available for performing the conventional lab tests necessary for determining them. With the aim of avoiding this problem, some structural integrity assessment procedures present a hierarchical scheme [2-4], which allows one to accommodate the kind of analysis to the quality of the material available data. Thus, there exist analysis levels that, although usually quite conservative permit evaluations to be carried out from a limited information about the material.

One of the tests which, according to its particular characteristics, is suitable for the determination of the properties of metallic materials required by those basic levels is the Small Punch Test. This test, fast and inexpensive is performed on a miniature specimen for which machining process requires a minimum amount of material (which normally does not put at risk the integrity of the structure).

In this paper, taking as a reference the Standard level or option of Fracture Module of the recently developed FITNET European Procedure [2], the methodologies needed for the estimation from Small Punch Tests of the properties required by the procedure have been established. In the development of these methodologies four materials have been used: three steels that cover a wide range of mechanical strengths –one Grade A ordinary ship building steel and two structural E690 and S460N steels- and a Al-Cu-Mg alloy. The proposed approach was finally validated by analysing the fracture of a real component.

The FITNET Procedure

The FITNET European structural integrity assessment procedure [2] is organised around four modules that correlate with the four most common failure modes of structures: Fracture, Fatigue, Creep and Corrosion.

The Fracture Module, heir of the SINTAP procedure [3], uses two analysis tools that can be chosen by the user and with which an equivalent result must be obtained. These tools are the Failure Assessment Diagrams (FAD) and the Crack Driving Force Diagrams (CDFD). The FAD, application of which is simpler than the CDFD, shows besides the advantage of the possibility of an integrated analysis of fracture and plastic collapse phenomena [5].

In the same way as SINTAP procedure, the FITNET presents a hierarchical structure, which means that it is organised in options as a function of the available information about the material or the required precision or conservatism level. Thus, the Basic Option, or Option 0, only requires very limited information of the material, but, at the same time, it is the option that, necessarily offers the most conservative results. So, the more available data of the material, the less conservative levels can be used in the analysis. One possible strategy for performing structural integrity assessments can be to start with the Option 1 which needs few resources (the procedure does not recommend the use of Option 0 except in those cases in which another alternative does not exist). If the result is acceptable, it is not necessary to continue with the analysis, but if not, one must go to the upper levels, but having already generated relevant information about the influence of the involved parameters in the results of the assessment. Table 1 summarises the tensile properties required by the assessment as a function of the analysis options.

Table 1. Required tensile properties as a function of analysis options [2].

Option	Title	Tensile data
0	Basic	σ_y
1	Standard	σ_y and σ_u
2	Mismatch	σ_y and σ_u of weld and parent materials
3	Stress-strain	Full stress-strain curve
4	J-integral	Full stress-strain curve
6	Constraint	Full stress-strain curve

In parallel with the options shown by Table 1, it is possible to carry out fracture assessments which take into account initiation or ductile tearing. As a function of the chosen route, fracture toughness data in the format indicated by Table 2 are needed.

Table 2. Format of fracture toughness data as a function of the type of analysis chosen [2].

Route	Format of toughness data
Basic option	Charpy energies
Initiation route	Fracture toughness at initiation, K_{IC}
Tearing route	Fracture toughness as a fuction of ductile tearing, J-R curve

Thus, according to Tables 1 and 2, for an initiation analysis following Standard Option, yield stress, tensile strength as well as a characteristic fracture toughness value must be known.

Small Punch Test (SPT)

The Small Punch test can be briefly described as a punch test over a small plane specimen deforming it until fracture. A scheme of the used device in these tests can be observed in Fig.1 [6].

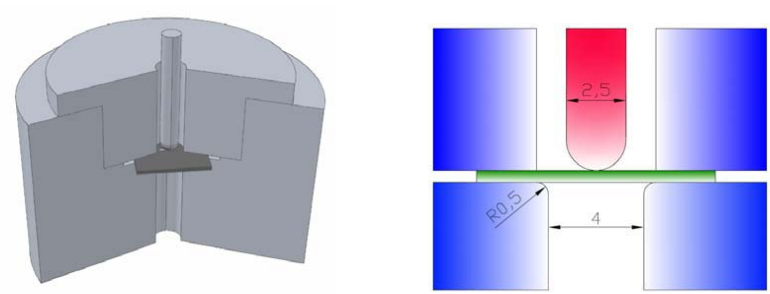

Figure 1. Scheme of the used experimental device.

During the test, the force applied and the displacement experimented by the punch are recorded in a continuous manner, obtaining a curve with the aspect of the one that is shown in Fig.2. From this test curve it is possible to obtain some parameters that can be correlated with the mechanical properties of the material. Thus, the force P_y, which indicated the initiation of the plastic processes, is usually correlated with yield stress [7-9], while P_{max} is linked to the tensile strength [10].

In this work, a plane specimen configuration of dimensions 10x10 mm and a thickness of 0.5 mm, has been used for the determination of tensile properties, while for the estimation of fracture toughness specimens with the same dimensions in which a lateral notch of known length and a radius of 0.15 mm [10] were machined have been employed. Fig. 3 shows a conventional specimen, without notch, and beside other with notch.

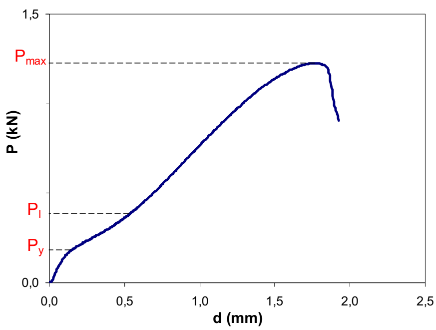

Figure 2. Example of experimental SPT curve

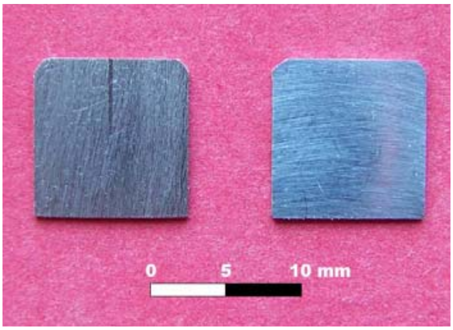

Figure 3. SPT specimens

Use of Small Punch Test in the Standard Option of FITNET procedure. Mechanical properties.

As it has been explained above, for performing structural integrity assessments following the recommendations of the Standard Option of FITNET procedure, yield stress, tensile strength and fracture toughness must be known. In this paper three methodologies for obtaining these parameters from Small Punch Tests are proposed.

Yield stress. The general Small Punch bibliography [7,8,10], admits that between P_y and σ_y there is a relationship of the type (1).

$$\sigma_y = \alpha \frac{P_y}{t^2}. \tag{1}$$

Where α is an empiric dimensionless coefficient and t is the thickness of the specimen.

In [9], an expression based on plates theory and keeping the basics of (1) is proposed for the estimation of the yield stress of the material (2).

$$\sigma_y = \frac{3 \cdot P_y (1+\nu)}{2\pi t^2} . \ln \frac{a}{r'} . \quad (2)$$

Where ν is Poisson`s coefficient, a is the hole radius of the lower die of the device and r' is the contact radius between punch and specimen.

The main limitation of these formula lies on the arbitrariness to define force P_y. Some authors propose the determination of this force as the intersection between the test curve and a parallel line to the first elastic part of test curve displaced a given value [12]. However, due to the indentation suffered by the specimen [10], specially marked in that first part of the curve, the determination of the slope of the elastic region is really complex. Nevertheless, in this initial part of the curve the existence of an inflexion point, necessarily linked to the initiation of plastic processes, has been observed. If P_y is defined as the force corresponding to this inflexion point, expression (3) which correlates P_y with the value of material's yield stress and based on (1) and (2) can be obtained.

$$\sigma_y = 1.16 \frac{P_y (1+\nu)}{t^2} . \quad (3)$$

The suitability of the proposed approach is remarked on Fig.4, where the estimated value according to (3) has been represented together with the actual yield stress values of the four analysed materials.

Ultimate tensile strength. Some authors [10] propose expressions of the type (4) in order to correlate the maximum load of Small Punch Test with material ultimate tensile strength.

$$\sigma_u = \alpha \frac{P_{max}}{t} . \quad (4)$$

By applying the relation (4) to the materials of this paper and with the best fit for adjusting parameter α, the result of Fig.5 is obtained. As it can be observed, the prediction does not exhibit too satisfactory results.

Taking into account the normalisation of the test curve developed in [6], expression (5) is proposed for the determination of tensile strength from the maximum load of Small Punch Test and force P_I, which is the force corresponding to the inflexion point that indicates the boundary between plastic and membrane stretching regimes [6].

$$\sigma_u = \alpha \frac{P_I}{t^2} + \beta \cdot \frac{P_{max} - P_I}{t} . \quad (5)$$

In (5) α takes the value of 0.23 and β is equal to 0.09 (mm^{-1}). Fig.6 shows, again, the predictions of (5) together with the actual values of ultimate tensile strength of the analysed materials, where it can be appreciated the improvement experimented with this new proposal.

Fracture toughness. There exist several methodologies oriented to the determination of fracture toughness from Small Punch Tests. Some of them [13,14] are based on correlations between Ductile-Brittle Transition Temperature, obtained from Small Punch Tests at different temperatures, and Charpy Transition Temperature, and, afterwards, using one of the available correlations of literature, this Charpy Transition temperature can be finally correlated with fracture toughness. This method, besides involving the uncertainty associated with the two empirical correlations, exhibits the experimental difficulty for reaching Small Punch Transition Temperature, in some cases even 300 K lower than Charpy Temperature [15]. Other methodologies for estimating fracture toughness from Small Punch Tests are based on performing Finite Element simulations which must incorporate damage models [16,17], but the high level of complexity of these methods rules them out as candidates for being used in lower levels of FITNET procedure.

In this paper, the methodology developed in [11] is proposed to determine fracture toughness. Attending to simple energetic considerations, it is suggested to estimate fracture toughness by using notched specimens (Fig. 3). Taking into account that, with this configuration of specimens the initiation of cracking was found in the surroundings of the maximum of the curve [11], evaluating the energy under the curve until that point and, finally applying equation (6) a value of fracture toughness characteristic of the initiation is obtained.

$$J_{0.2} = \frac{C \cdot U_{max}}{b \cdot B}. \tag{6}$$

In (6), U_{max} is the energy absorbed by the specimen until the value of maximum load in the test, B is the specimen thickness and b is the reaming ligament. C is a semi-empiric coefficient that can be calculated according expression (7).

$$C = 0.12 + 58 \cdot \frac{(a-3)}{\sigma_Y}. \tag{7}$$

Where a is the length of the specimen notch and σ_Y is flow tension of the material, in MPa which can be defined as the average value between yield stress and ultimate tensile strength.

The value estimated by (6) in terms of J, can be expressed in units of K by applying the equation (8) [18].

$$K_J = \sqrt{\frac{J \cdot E}{(1+\nu^2)}}. \tag{8}$$

In Fig. 7 the values estimated according (6) and (8) can be observed together with the values of toughness for Grade A and E690 steels obtained by conventional means. Finally, Table 3 summarised the values of mechanical properties obtained by means of Small Punch Test and by conventional tests for each one of the analysed materials.

Validation

With the aim of validating the methodologies developed for the estimation of the properties needed in a structural integrity assessment according to Option 1 of FITNET, a three point bending test was performed over a specimen with Charpy configuration [19]. This specimen, of a material of unknown properties, was previously precracked (initial crack equal to 4.14 mm). The test was carried out until fracture (Fig. 8), which occurred for a load of 9.027 kN. Afterwards, from one of the broken halves, 3 conventional Small Punch specimens were machined for the estimation of tensile properties, and 3 other notched Small Punch specimens (initial length of notches, a=4.75 mm) for the determination of fracture resistance. The results of these tests, after applying the previously described methodologies are summarised in Table 4.

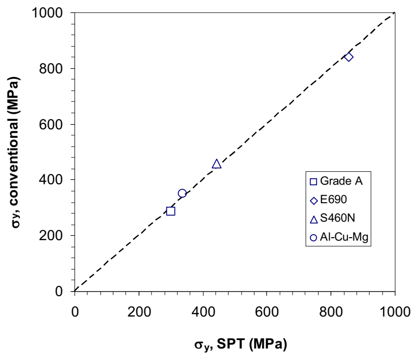

Figure 4. Yield stress, SPT vs. Conventional tests

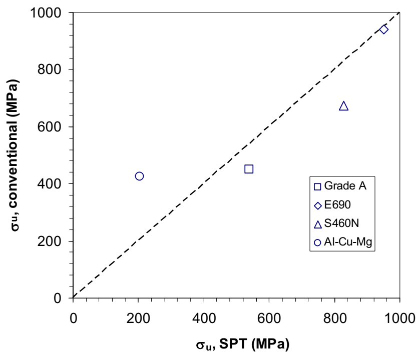

Figure 5. Ultimate tensile strength, SPT vs. Conventional tests [7,8, 10]

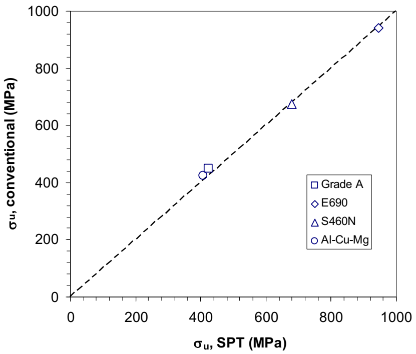

Figure 6. Ultimate tensile strength, SPT vs. Conventional tests, proposed approach

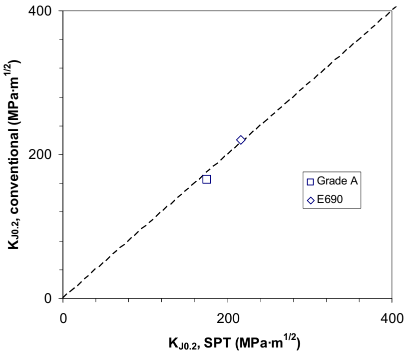

Figure 7. Fracture Toughness, SPT vs. conventional tests

Table 3. Comparison of results of conventional tests and Small Punch Tests

	σ_y [MPa]		σ_u [MPa]		$K_{J0.2}$ [MPa·m$^{1/2}$]	
	Conv.	SPT	Conv.	SPT	Conv.	SPT
Grade A	288	301	450	425	165	175
E690	840	856	940	945	220	216
S460N	460	443	675	679	--	--
Al-Cu-Mg	350	337	425	408	--	--

Table 4. Mechanical properties of the material for validation

σ_y [MPa]	σ_u [MPa]	$K_{J0.2}$ [MPa·m$^{1/2}$]
450	551	219

In the validation process, the route of Failure Assessment Diagrams (FAD) was chosen for performing the analysis. Thus, the assessment consisted of drawing in the FAD the point that represents the failure of the component according to the non-dimensional variables K_r and L_r, which are defined by equations (9) and (10).

$$K_r = \frac{K_I}{K_{mat}}. \tag{9}$$

$$L_r = \frac{P}{P_y}. \tag{10}$$

Where K_I is the Stress Intensity Factor for the studied geometry and whose solution can be consulted in the compendium of FITNET procedure [2], K_{mat} is the characteristic value of initiation of fracture toughness, P is the applied load and P_y is the load able to cause the failure by plastic collapse for the given geometry (P_y is also a function of yield stress) and its solution is also included in the annexes of FITNET [2]. The result, for the conditions of load under fracture and for the properties estimated by Small Punch Tests, is K_r=0.40 and L_r=1.64.

The definition of Failure Line which, in the FAD, delimits the safe zone and the non-safe region was done in accordance with the expressions of Option 1 of FITNET (11-13). Besides, and following the recommendations of the procedure, the expressions corresponding to a material with discontinuous yielding which, in absence of information about the form of tensile curve, give conservative results, were chosen.

$$f(L_r) = \left[1 + 0.5 \cdot (L_r)^2\right]^{-1/2}. \qquad L_r \leq 1. \tag{11}$$

$$f(1) = (\lambda + 1/2\lambda)^{-1/2}. \qquad Lr = 1. \tag{12}$$

$$f(L_r) = f(1) \cdot L_r^{(N-1)/2N}. \qquad 1 \leq L_r \leq L_r^{max}. \tag{13}$$

L_r^{max} is defined by (14), while parameters λ and N are defined respectively in equations (15) and (16).

$$L_r^{max} = 0.5 \cdot (1 + \sigma_u/\sigma_y) \tag{14}$$

$$\lambda = (1 + E \cdot \Delta\varepsilon/\sigma_y) \tag{15}$$

$$N = 0.3 \cdot [1 - (\sigma_y/\sigma_u)] \tag{16}$$

The deformation corresponding to Yield Plateau, which appears in equation (15), can be estimated following FITNET procedure with (17).

$$\Delta\varepsilon = 0.0375 \cdot (1 - \sigma_y/1000) \tag{17}$$

In Fig. 9, the FAD of this validation example is shown, where the point which represents the fracture conditions lies in the non-safe area as must happen in a failure case. The location of the point remarks the fact that the failure driving factor should have been plastic collapse, which is in good agreement with the observations of the real test (Fig. 8). The safety factor took an approximate value of 1.5.

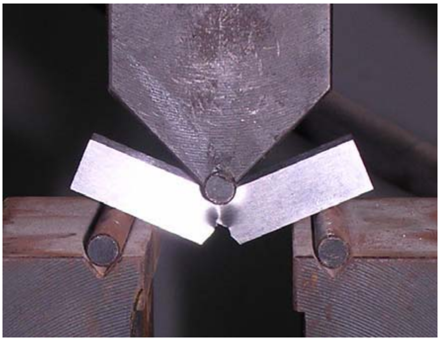

Figure 8. Validation test

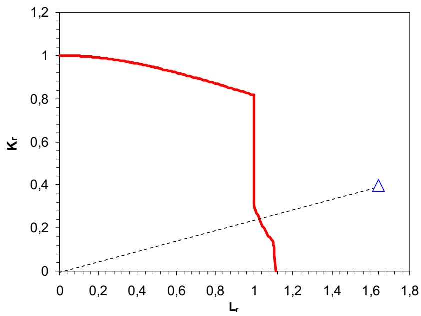

Figure 9. FAD of the validation example

Conclusions

In this paper, the methodologies for estimating, by means of Small Punch Tests, those mechanical properties required by European Procedure FITNET for structural integrity assessments have been established. Three methodologies have been developed for determining yield stress, ultimate tensile strength and fracture toughness of metallic materials. The proposed methods have been validated by means of the analysis of the failure of a Charpy specimen after performing a three point bending test, and the results were fully satisfactory and exhibited a reasonable safety factor.

Thus, the Small Punch Test, from now onwards, can be considered as an alternative to standard test methods for obtaining the properties required by structural integrity assessments, with the additional advantages of being a fast and inexpensive test which demands minimum material amounts, and as it has been proven, fully reliable.

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