CONSIDERATIONS IN SELECTING LABORATORY SCALE TEST SPECIMENS FOR EVALUATION OF FRACTURE TOUGHNESS

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Abstract: The assessment of defects in large steel structures requires a trustworthy evaluation of the material's toughness. This toughness is not only a material property but is also influenced by the loading conditions and geometry; the so-called constraint. The resulting representative value is referred to as the apparent toughness.

The evaluation of apparent fracture toughness in a flawed structure is preferentially performed through laboratory scale testing, as full scale tests are both expensive and often challenging to perform. Several laboratory scale test specimens are available, among which a Single Edge Notch Bending specimen, Single Edge Notch Tensile specimen, Double Edge Notch Tensile specimen and Centre Cracked Tensile specimen. Each of these specimens has its own specific constraint. Therefore, the selection of an appropriate test specimen is of primary importance for limiting the conservatism and avoiding potential unconservatism with respect to full scale behaviour.

This paper provides a general framework to select an appropriate test specimen based on detailed finite element simulations of both the full scale structure and the laboratory scale test specimens. These finite element calculations allow for a characterization of the crack tip stress fields in both situations. Different theoretical frameworks are available for this characterization; the *Q*-parameter is considered in this paper. To demonstrate the applicability of this procedure, an example case is presented for circumferentially oriented defects in pressurized pipelines under longitudinal tension.

It is concluded that the presented framework allows for efficiently selecting a laboratory scale test specimen, which enables to evaluate the apparent fracture toughness for a given large scale structure. The obtained toughness can thus be incorporated in analytical flaw assessment procedures, reducing the degree of conservatism. This in turn allows an economically effective design.

Keywords: Apparent toughness; constraint; finite element analysis

1 INTRODUCTION

Several standards are available for the integrity assessment of defects (e.g. BS 7910, API 579 [1, 2]). Most standards rely on the use of the Single Edge Notched Bend (SENB) or Compact Tension (CT) specimen for the evaluation of the fracture toughness. It is, however, widely known that the tearing resistance is strongly influenced by the constraint ahead of the crack tip [3]. This is the triaxiality, which is influence by the loading condition and geometry of the specimen. Hence the term apparent toughness is introduced, which implies that the toughness is no longer a material property but also depends on the geometry and loading conditions, i.e. the constraint level. The use of SENB or CT specimens results in lower bound toughness values, as these test specimens represent high constraint conditions [4]. Accordingly, a defect assessment based on these test results will often be overly conservative. To reduce or eliminate this conservatism, a more suitable test specimen might be selected based on the actual structural situation.

This paper presents a framework to select an appropriate test specimen, considering the constraint in the actual structure and a variety of laboratory scale test specimens. This framework is presented in section 2. By means of example, it is applied to select an appropriate test specimen for the assessment of circumferentially oriented pipeline defects in section 3. Conclusions are presented in section 4.

2 FRAMEWORK

2.1 Laboratory scale test specimens

Several test specimens are commonly considered in fracture mechanics test laboratories (Figure 1). Preference should be given to standardized configurations, e.g. SENB or CT specimens. However, these only represent high constraint conditions. Therefore, other commonly reported configurations could also be considered. The most frequently reported ones are listed below:

- Single Edge Notched Tension (SENT): several different configurations of the SENT specimen are reported. An important difference relates to the loading condition; rotation in the end grips might be restricted (i.e. clamped conditions: $SENT_c$) or free (i.e. pinned conditions: $SENT_p$).
- Double Edge Notched Tension (DENT)
- Centre Cracked Tension (CCT)

For all above specimens, the thickness is most commonly taken equal or as close as possible to the wall thickness. This is of particular interest for materials with pronounced heterogeneity through thickness (such as welds). Another relevant property is the defect depth relative to the width (a/W), which is often varied in order to change the constraint or improve the measurability of for instance the crack mouth opening during testing. Next to this set of specimens, certain research areas consider specimens devoted to specific applications. As such, the Curved Wide Plate (CWP) test is commonly reported for pipeline girth weld testing [5, 6].

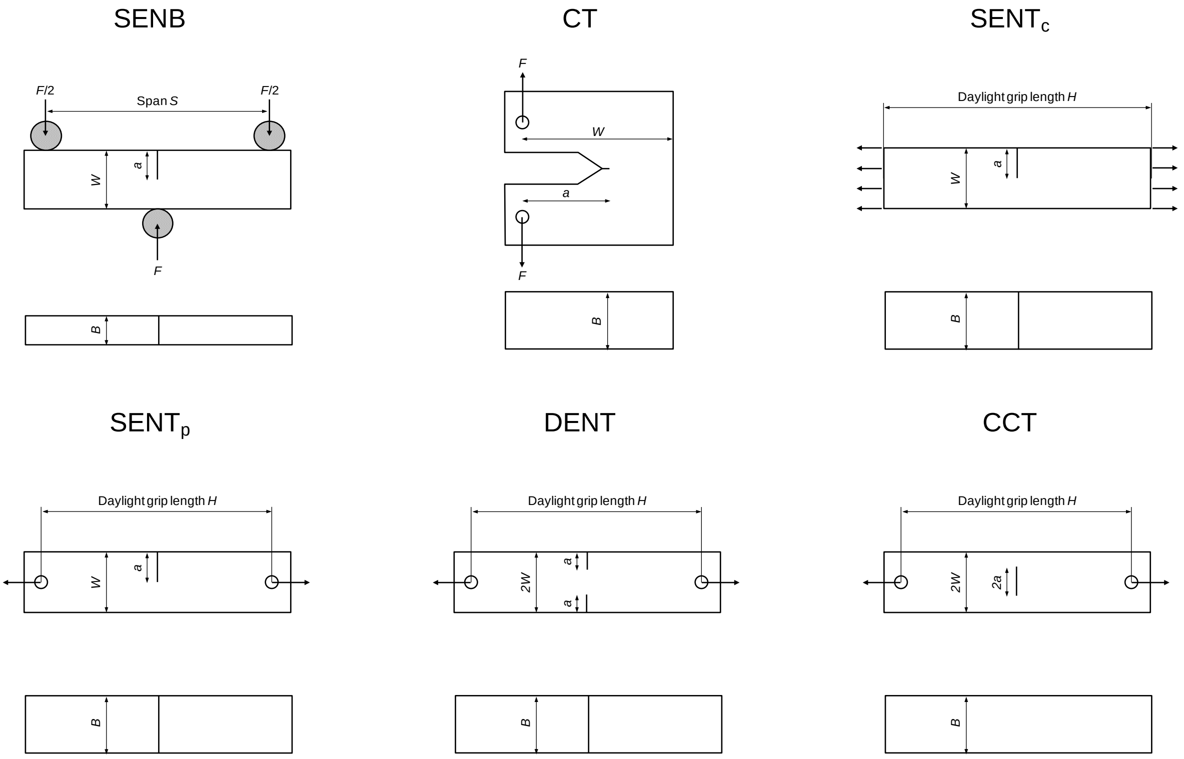

Figure 1 Common test configurations for laboratory scale test specimens

2.2 Constraint evaluation

To evaluate the potential difference in constraint between the laboratory scale test specimens and the final application, several theoretical frameworks have been developed for a quantitative evaluation of the constraint based on the magnitude of the crack tip stress fields. To this purpose, a second, so called constraint parameter, is introduced next to the crack driving force. This parameter characterizes the potential difference between the crack tip stress fields at a similar crack tip loading, in terms of the applied J-integral or K_I. The selection of such theoretical framework depends on the final application. In brief, the following guidance can be given towards the selection of an appropriate framework:

- *K-T theory*: this two-parameter framework was originally developed for the characterization of crack tip stress fields in the linear elastic fracture mechanics regime [7]. Nowadays, the originally used stress intensity factor K_I is often replaced by the J-integral and the application extended towards elastic-plastic fracture mechanics. A sound theoretical base is however missing, making the use of this *J-T* framework debatable under elastic-plastic conditions.
- *J-Q theory*: originally developed by O'Dowd & Shih in the early 1990's [8, 9], this framework compares the crack tip stress field at a given distance to a reference stress field. Originally, this reference stress field was obtained from analytical formulae (the HRR solution). Later on, it was often determined using a Modified Boundary Layer (MBL) model, which implies that random material properties could be selected. However, as the comparison only considers the crack tip stresses at one selected location, the self-similarity between the actual and reference crack tip stress fields needs to be evaluated. Remark that this theoretical framework was intentionally developed for elastic-plastic conditions.
- *J-h theory*: instead of comparing the crack tip stress field to a reference field, this methodology evaluates the stress triaxiality (h) ahead of the crack tip at a given distance. This simplifies the evaluation as no reference stress field is to be determined. Furthermore, an excellent correspondence between the Q-parameter and h is reported in literature [10].
- *J-A_2 theory*: this framework was also developed for elastic-plastic conditions [11, 12]. In accordance to the *J-Q* framework, the stress field obtained through finite element simulations is compared to the HRR solution. However, in this case the constraint parameter is not evaluated at a single distance but obtained through a least squares fit over a certain range ahead of the crack tip.

From the above description, it is clear that a basic distinction is to be made between linear elastic and elastic-plastic conditions. The former is preferably assessed using the *K-T* theory, whereas the other approaches might be considered for the latter.

2.3 Selection of test specimen

An overview of the selection process is given in Figure 2. First, the actual problem needs to be well defined in terms of geometry and loading conditions. The latter implies load level and load directions. Second, a pool of potential laboratory scale test specimens should be composed, as outlined before in §2.1. Accordingly, finite element models are required for the actual structure as well as the preferred laboratory scale test specimen(s). The crack tip stress fields are obtained for all models by means of simulations. To this purpose, special attention should be directed to the mesh design in the vicinity of the crack tip. An accurate evaluation of the crack tip stress fields requires a gradually coarsening and sufficiently fine spider web mesh. Using the obtained crack tip stress fields, the selected constraint parameter can be evaluated for all configurations. This evaluation is performed over a realistic range of load levels, resulting in a constraint trajectory (e.g. Q as a function of J).

As the constraint trajectories of the structure and the laboratory specimens are known, their relative differences can be assessed. Under optimum conditions, the laboratory scale specimen shows a close to identical constraint trajectory. However, as a more generalized situation, this will not be the case. The laboratory specimen trajectory should not have a lower constraint compared to the actual structure. Such situation implies a potentially unconservative assessment. On the other hand, overly conservative assessments should be avoided. Therefore, it is advisable to start from a variety of test specimens, allowing for a qualitative comparison. This will eventually result in a ranking of the selected test specimens.

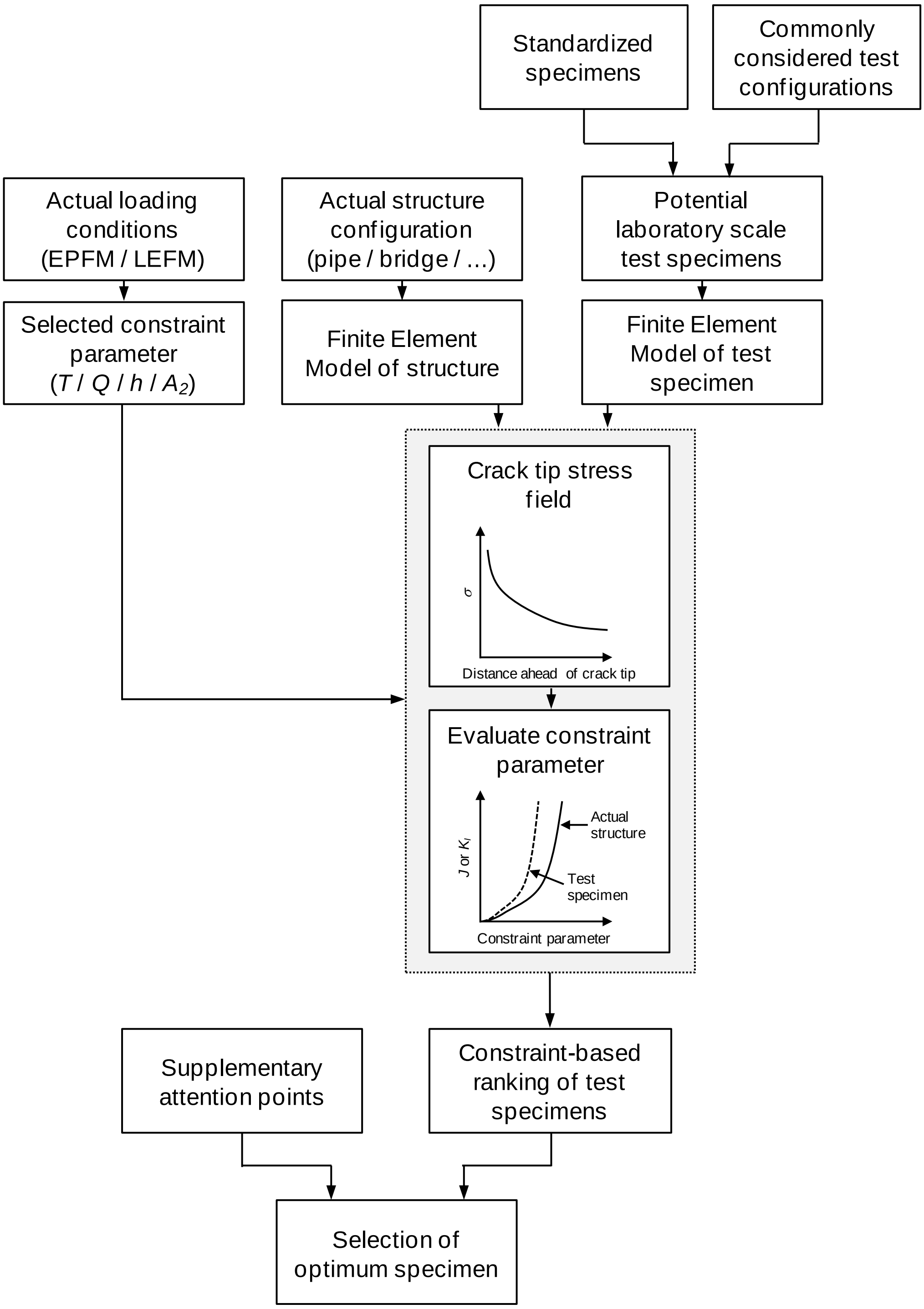

Figure 2 Schematic overview of test specimen selection based on constraint characterization

However, in the decision process some supplementary attention points need to be addressed:

- *Thickness reduction*: in general the thickness reduction should be minimized. This is particularly the case for those materials having strongly heterogeneous properties through the thickness. This can for instance be expected for irradiated materials or welds.

- *Availability of required test apparatus/capacities*: As the primary aim is to test full wall thickness specimens, the required test capacity clearly depends on the specimen geometry and loading conditions. It is for instance known that SENB testing requires far lower test capacities compared to SENT testing. Furthermore, some tests require special mounting devices (e.g. hydraulic grips).

- *Amount of material needed for testing*: The amount of material needed for one test will influence the cost of the tests. Sampling a larger amount of material will increase the required test capacities, but also gives the potential to capture the material heterogeneity better. This is particularly of interest for applications where failure is expected to be dominated by a weakest link mechanism (e.g. brittle fracture). Additionally, a larger width of the tested section is likely to represent the actual conditions more accurately, since a localized deterioration of the material properties not necessarily results in a poor overall behaviour. For instance, a single local brittle zone might dramatically reduce the tearing resistance in small scale testing. However, if surrounded by sufficiently ductile material, a satisfactory outcome can be expected from a large scale test (e.g. CWP testing for pipeline applications).

- *Availability of test standards*: preference should be given to specimens for which standardized procedures are available. Not only will the results of these standardized tests more easily be accepted by the international community, the interpretation of the results will also be better described in literature, which facilitates their exchangeability. For instance, if crack growth is to be monitored by means of the unloading compliance technique, a transfer function is required to relate the compliance to a defect length. New equations need to be established via (elastic-plastic) finite element simulations, if these are not available in standards or open literature.

Based on the abovementioned criteria an optimum test specimen is subsequently proposed, which is conservative from a constraint point of view and suitable for the considered test laboratory.

3 CASE STUDY: PIPELINE GIRTH WELD DEFECTS

3.1 Problem statement

Within this case study circumferentially oriented pipeline defects are assessed. The commonly detected defect sizes vary both in depth and length. However, for this study only a single defect with a fixed depth (*a*) equal to 3 mm and a length (2*c*) equal to 50 mm is studied, for a pipe with a diameter (*D*) of 1016 mm (40'') and a wall thickness (*t*) of 15 mm.

First, the actual loading and geometry conditions need to be defined. Within this example case a pressure free pipe is studied. This pipe is however subjected to large (plastic) longitudinal deformations. The above loading conditions could resemble the installation through reeling of a pipeline with a part through defect.

Second, a selection of potential test specimens is made. All previously discussed specimens are considered, apart from the SENB and CT specimen as it is well known that their constraint is significantly higher than is the case for pipes [13, 14]. In addition to these specimens, the Curved Wide Plate (CWP) specimen is considered (Figure 3).

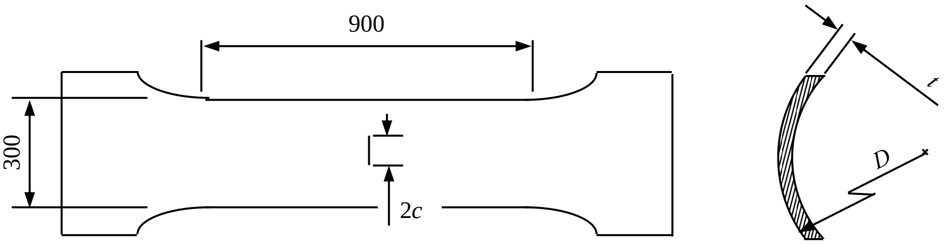

Figure 3 Schematic representation of Curved Wide Plate specimen

For all above specimens, in-house developed Python scripts allow systematically generating and analyzing a representative and well validated finite element model [15-17]. These models have a gradually coarsening spider web mesh surrounding the initially blunted crack tip with a root radius equal to 2.5 µm. The exact dimensions are listed in Table 1. The thickness of all specimens was taken equal to the wall thickness of the pipe, although in practice a thickness reduction will be needed seen the curvature of the original pipe.

Table 1 Geometrical properties of considered specimens

Parameter	Value
t	15.0 mm
D	1016 mm (40”)
W	15.0 mm
B	15.0 mm
a	3.0 & 7.5 mm (*)
c	25.0 mm

(*) except for CWP and pipe specimens: solely 3.0 mm

The considered pipe has a yield strength (σ_0) of 400 MPa, Young’s modulus of 200 GPa and Ramberg-Osgood strain hardening exponent of 10.

3.2 Constraint evaluation: *J*-*Q* calculations

The *J*-*Q* theory is arbitrarily selected within this paper as both the *J*-*Q*, *J*-*h* and *J*-A_2 approach are equally suitable for the presented problem.

Within the *J*-*Q* theory, the crack tip opening stresses perpendicular to the crack ($\sigma_{\theta\theta}$) are compared to a reference field ($\sigma_{\theta\theta;ref}$) obtained from a well validated MBL model [16]. The *Q*-parameter is subsequently defined as the normalized difference between both stress fields:

$$Q = \frac{\sigma_{\theta\theta} - \sigma_{\theta\theta;ref}}{\sigma_0} \tag{1}$$

This difference is evaluated at a normalized distance ($\bar{r}$) equal to two ahead of the crack tip, in the cracked plane:

$$\bar{r} = \frac{r}{J/\sigma_0} = 2 \tag{2}$$

Remark that low *Q*-values indicate low constraint conditions (i.e. high apparent toughness). For the selected specimens, the resulting *J*-*Q* trajectories are shown in Figure 4, with negative *Q*-values plotted on the x-axis. By means of reference the *J*-*Q* trajectory obtained for the pipe specimen is plotted as a solid line, the dotted lines represent the considered laboratory test specimens with varying initial crack depths. All specimens show a pronounced loss of constraint as plasticity develops, indicated by low *Q*-values. A more pronounced loss of constraint results in a higher resistance curve. Accordingly, it is concluded that specimens are conservative as long as their *Q*-values remain higher than the pipe specimen. Furthermore focusing on SENT specimens, it is noted that the influence of the boundary conditions, i.e. clamped versus pinned, is most pronounced for deeply notched specimens. This is in agreement with results published by Cravero et al. [18]. The DENT specimens also show a slight influence of the defect depth. For CCT specimens no significant influence of the relative crack depth is observed. Finally, the constraint in the considered CWP specimen is in excellent agreement with that of the pipe, as could be expected from previous analyses [19].

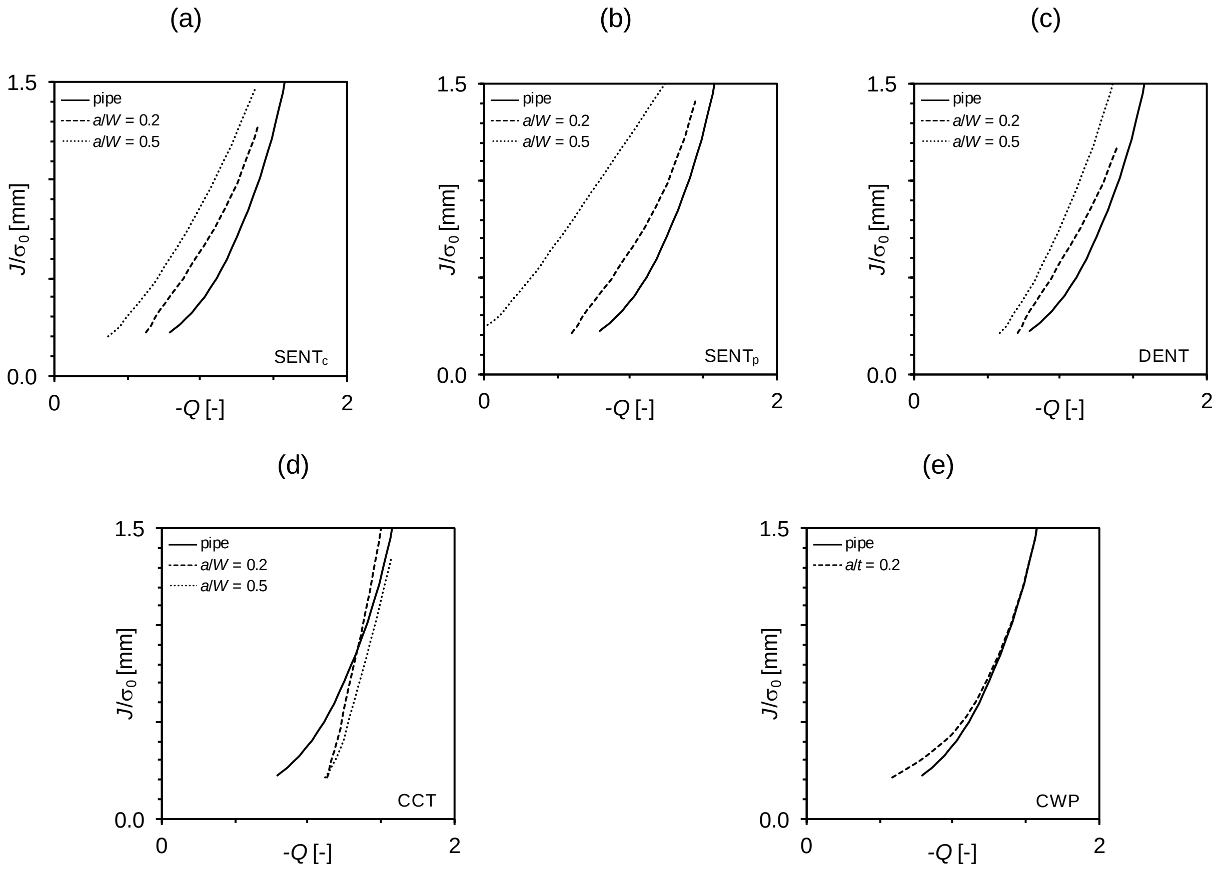

Figure 4 *J-Q* trajectories for selected laboratory test specimens

3.3 Selection of test specimen

Based on the constraint calculations and considering the requirements listed in §2.3 a suitable test specimen can be selected for the considered pipeline defect. First, an unconservative assessment is to be avoided. Accordingly, the use of CCT specimens is discouraged as their constraint is lower than for the pipe. On the other hand, the pin loaded SENT specimen shows a significantly higher constraint compared to the pipe specimen. This is particularly the case for the deeply notched specimen. Accordingly, this specimen should not be selected either.

As already noted in §3.2 the constraint in the CWP specimen almost perfectly matches the constraint in the pipe specimen. This suggests the CWP specimen is an optimum alternative. In addition, by performing a CWP test, the strain capacity can additionally be determined. However, CWP testing has two major drawbacks:

- The required test capacities for CWP testing are significantly higher compared to small scale testing. Accordingly, the cost going with and the complexity of the test increases. This is of secondary importance for large projects but might be crucial for routine testing.
- No standardized equations are available for the interpretation of the test data. Specialists are therefore required to interpret the test results. For instance, detailed finite element studies are required if the amount of ductile crack extension is to be known at each stage of the test.

Accordingly two types of specimens remain suitable for small scale laboratory testing, i.e. DENT and clamped SENT. For both specimens, the amount of material tested is significantly smaller compared to the CWP specimen. This implies that the test results will be more susceptible to variations of the material properties, therefore necessitating a larger number of tests before statistically significant conclusions can be drawn [20]. From the constraint point of view, the DENT specimen most closely approximates the defect in the pipe. On the other hand, the required test capacity for (clamped) SENT testing is only half of the required capacity for DENT testing. Consequently, the required amount of test material per test is higher for DENT testing. Furthermore, the thickness reduction is more pronounced for DENT testing. Although this has not been explicitly accounted for in this study, the final specimens need a rectangular cross section fitting the originally curved pipe. Accordingly, the longer the arc-length of the specimen, the more the thickness needs to be reduced. This should be considered as most circumferentially oriented defects in pipes are located near the girth welds, which are known to be of a strongly heterogeneous nature [21, 22]. At last, it is noted that the preparation and analysis of DENT specimens is more challenging, as two different cracks need to be monitored. Therefore, it is concluded that SENT testing is preferential over DENT testing for small scale laboratory testing.

In conclusion, the CWP specimen is preferred as a test specimen for larger projects and for those laboratories having large scale test facilities. If this is not the case, the clamped SENT specimen can be selected as a suitable small scale alternative. However, a larger number of SENT tests should be considered in order to capture scatter in the material data.

4 CONCLUSIONS

A generally applicable method is presented to select a suitable laboratory scale test specimen for determination of the apparent fracture toughness, taking in consideration the constraint developing in the actual structure. Several theoretical frameworks can be considered to quantify the constraint. Directions are provided for selecting an appropriate framework, depending on the intended application. In addition, attention should be paid to the amount of material required for testing as well as the required test capacities.

A selected framework, based on the *J-Q* theory, was applied for the selection of a suitable small scale specimen for the assessment of a circumferentially oriented defect in a large diameter transportation pipeline, subjected to large (plastic) deformations. In this case the constraint in the CWP specimen almost perfectly matches the constraint in the pipe. If however the test capacities are limited, SENT testing is a suitable small scale alternative provided that a sufficient number of tests is performed.

5 NOMENCLATURE

a	defect depth	mm
c	half defect length	mm
W	specimen width	mm
B	specimen thickness	mm
t	pipe wall thickness	mm
D	pipe diameter	mm
Q	constraint parameter	-
J	J-integral	N/mm
σ_0	Yield strength	N/mm²

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