DEFECT ASSESSMENT BASED ON GROSS SECTION YIELDING IN WIDE PLATE TESTS

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ABSTRACT

A brief outline is given of the applicability of wide plate testing for the assessment of the significance of defects on failure behaviour for notch ductile materials. Wide plate test results are assessed using the Gross Section Yielding concept. This concept aims to define a maximum tolerable defect size a_{gy} for gross section yielding before fracture ensues. The examples given illustrate that this approach permits a realistic assessment of the integrity of structures serving an important safety function.

KEYWORDS

Fracture mechanics, wide plate testing and gross section yielding.

INTRODUCTION

In assessing how welds and weld defects might affect fitness for purpose, it is seen from literature that one relies either on test results obtained from small test specimens (such as Charpy-V specimens) and/or intermediate scale tests (such as the CTOD tests). However, these approaches, which are to be considered as a final goal, may pose serious problems. The range of problems to which the existing methods are applied, can be divided into two categories.

The first category includes these cases where the final decision depends upon the required impact properties. Most people feel uneasy about applying the criteria established for C and C-Mn steels (upon which most codes are based) to modern materials. Indeed, it is common practice that most requirements arbitrarily either edge up the required impact values or lower the minimum testing temperature without adequate justification from full scale behaviour.

The second category includes these cases where the application of single notch tip fracture toughness parameters such as CTOD, J.. is recommended. Again , the engineer feels unhappy about a generalisation of the defect tolerance calculation methods, which are - mainly for analytical reasons -, always the result of simplifications of the real problem. In this connection, it can be asked whether e.g. the CTOD design curve approach may be extrapolated to notch tough materials, without considering a coherent basis similar to the ones on which the original work was based on.

As a consequence the author believes that for modern and tough materials the engineering significance of defects with regard to fracture initiation and propagation may not always be quantified by fracture mechanics methods directly, without making reference to full scale behaviour. Especially for high performance and expensive structures a widespread adoption of fitness for purpose approaches based on fracture mechanics requires a more detailed knowledge of the safety factors. Only then unnecessarily cautious predictions and uneconomical solutions can be avoided. Therefore, we are inclined to advocate the need for tests e.g. wide plate tests, resembling the actual structural detail and which are subjected to conditions that might be regarded as similar to those encountered in service.

Although the wide plate test does not correlate exactly with service experience, it answers at least a lot of puzzling questions with regard to the fitness for purpose philosophy. Following this line of thought, it is almost self-evident that once we are prepared to utilize the actual material properties (which differ from the idealized perfectly elastic-plastic characteristics) in ductile strain hardening materials the advantages of large scale testing with regard to fitness for purpose are indeed numerous - Denys (1). Moreover, the author realizes that the recommendation for wide plate testing applies only for important and expensive structures.

The assessment of wide plate test results to prevent the occurrence of unexpected and sudden failures in engineering structures and components has been the subject of intensive research at the Gent University. Based upon the progress which has been achieved and the knowledge of the many factors influencing a reliable and non conservative assessment of defects, an overall assessment concept has been developed. By applying the concept of "Gross Section Yielding" (GSY) to situations in which the elastic-plastic fracture mechanics is either invalidated or over conservative by excessive yielding (i.e. yielding beyond the so called plastic collapse behaviour), it will be shown hereinafter that this approach offers an opportunity to examine and apply fitness for purpose principles in a more practical sense.

ASSESSMENT OF WIDE PLATE TEST RESULTS

The wide plate test results are normally used to confirm the validity of defect tolerance calculations from small scale data. For this purpose, reference is frequently made to the most widely applied method in the elastic plastic regime: the CTOD design curve. However, serious problems arise when the wide plate test exhibits fully ductile behaviour. In these cases it is suggested to assess failure prediction by plastic collapse. The adopted methods for dealing with plastic collapse are ill-defined with respect to tolerable defect size estimations. To overcome the limitations

it is proposed to judge the wide plate behaviour in quite a different manner.

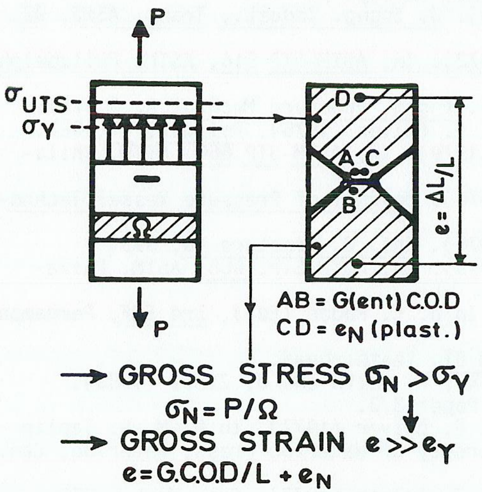

Fig. 1. Schematic representation of Gross Section Yielding.

It is evidently much more realistic to look for criteria which relate to practical behaviour and which are easy to use. In the author's opinion, the estimation of safety, the significance of defects, and thus service performance, must be directly related to the overall behaviour. The assessment of overall behaviour can only be based on either gross strength or gross ductility. For convenience, it is preferable to look for strength, and if we claim a gross strength of at least yield point magnitude we automatically obtain a good overall ductility. The philosophy behind this requirement is explained in Figure 1, and is based on extensive experimental work carried out at the Gent University. The method for assessing wide plate test results is referred to as the "Gross Section Yielding" approach.

GROSS SECTION YIELDING CONCEPT

The origin of the Gross Section Yielding approach is based on the employment of full thickness wide plate specimens containing a notch. The notch is located in that area of plate where high deformations will occur and in these regions where low toughness values are to be expected. The notched wide plate specimen is subsequently subjected to a tensile load at the minimum operating temperature. The use of full thickness ensures further that the constraint in the specimen matches that in the structure.

The experience in using this testing method for various kinds of materials and defect geometries (through thickness-, surface and buried defects), revealed that three distinct deformation modes can occur. The net section stress at fracture either exceeds the material's uniaxial yield stress (0.2 % proof stress) and the flawed wide plate specimen deforms by NET or GROSS section yielding. Or the net section stress at fracture is below the uniaxial yield stress, so that only CONTAINED yielding occurs - see Figure 2. The analysis of these deformation modes in relation with decreasing crack dimensions indicates that tough materials deform either by GSY or by NSY, whilst for less tough materials the sequence of deformation modes to be considered are GSY, NSY, CY and NSY. This difference may be explained by the plate width effects (1) Apart from the apparent plate width effect, it is obvious that for both situations a shift from GSY to NSY exists.

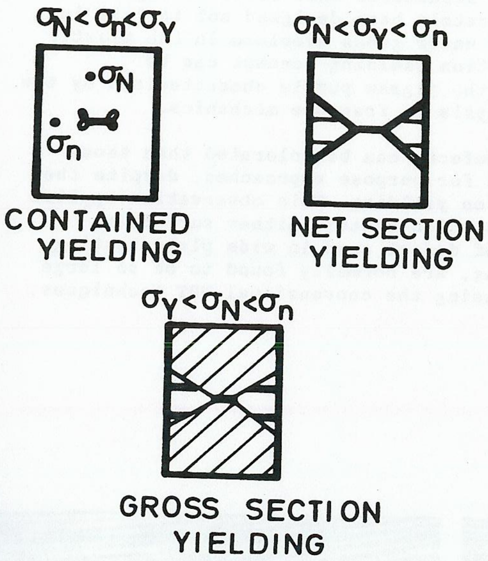

Fig. 2 CONTAINED, NET and GROSS section yielding.

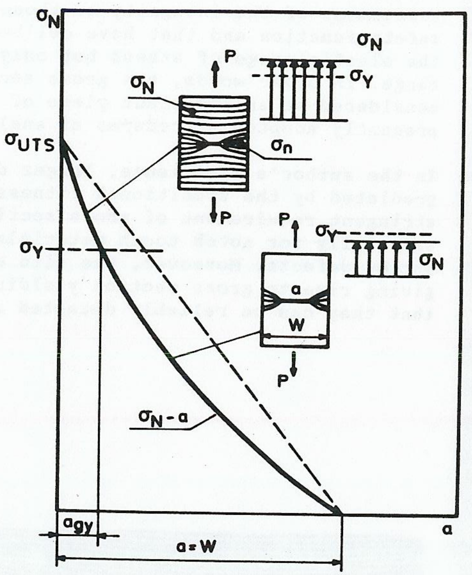

Fig. 3 Gross stress dependence of crack length.

These observations led to the consideration of a direct approach of defect tolerance, solely based upon wide plate testing . The demarcation between NET to GROSS section yielding permits estimation of the maximum tolerable defect size for gross section yielding a_{gy}. (Fig.3). Thus, a defect smaller than a_{gy} induces gross section yielding guaranteeing a good overall elongation and a strength of at least yield point magnitude. Consequently it can be construed that defects smaller than a_{gy} are acceptable. At this stage, we must emphasize that we utilize and assess the actual material properties for safety assessments in notch tough strain hardening materials, and that we do NOT allow gross yielding in the structure.
We only utilize the deformation phenomenon observed in wide plate test specimens to define acceptable defect sizes.
Moreover, the possibility of gross section yielding may be considered as a safeguard in case of e.g. accidental overloading.

METHOD OF APPLICATION

Since the purpose of this paper is not to acquaint the reader with all the experimental details of wide plate testing, only the general outlines will be described hereinafter. To apply the GSY concept the following experimental data are required:

1. The uniaxial yield strength of the (parent) material at the minimum operating temperature.

2. The ultimate tensile strength of the defective region (i.e. from the material containing the defect - only necessary for the determination of a_{gy} - see also further)
3. The gross stress at fracture (i.e. the load at fracture/gross section) of the wide plate specimen.

The maximum tolerable defect size a_{gy} is that at which the gross section failure stress equals the yield stress of the plate (Fig. 3).

The method has also been developed to incorporate consideration of transverse weldments and to cover through thickness surface and buried defects - Denys (2, 3). It should be noted that for the cases of transverse welds, in which both HAZ and weld metal overmatch the parent plate in yield stress , it is in principle only necessary to exceed the yield stress of the parent material to achieve gross section yielding.

It should be emphasized that the gross section yielding concept is not always applied to define the maximum tolerable defect size a_{gy}. It is rather intended to check whether a particular defect can be safely left in a structure.

For instance, in case the notch toughness (code) requirements (such as C_V or/and CTOD) are not achieved and as soon as the material used has strain hardening properties, it can be justified to apply the GSY concept. In these circumstances, it is considered that a defect can be present, even when NDT reveals no defects, so that the evaluation will be recategorized in a fitness for purpose approach. For this purpose, a large scale or wide plate test with a defect of detectable size will be carried out in order to check wether gross section yielding can be obtained. If that is the case, it is the experience that a code relaxation can be discussed with the governmental quality control authorities.

Finally, the GSY concept, as it stands, is currently applied to assess defects in structural elements such as pipes, storage tanks, plate and nozzle intersections, etc ...

PRACTICAL APPLICATION

The following example illustrate the application of the method just described.

Check whether buried defect of 10mm x 50mm and a continuous embedded defect 10mm x 350mm located in the HAZ of 30 mm thick welded StE 355 plates are acceptable (t= -20°C). The following general data are available - Denys, Musgen (4).

The submerged arc welding procedure, with K preparation, was used (as it was envisaged to sample the HAZ only). The heat input was 2,5 kJ/mm. No PWHT was applied.

The weld metal yield strength approximately matches that of the plate. The mechanical properties at -20°C as determined on wide plate specimens of plain material gave a yield strength of 425 N/mm^2 and a σ_u of 629 N/mm^2. The minimum CTOD values at -20 °C (specimen size 2BxB) for HAZ and plate material were 0.23 mm and 0.96 mm respectively.

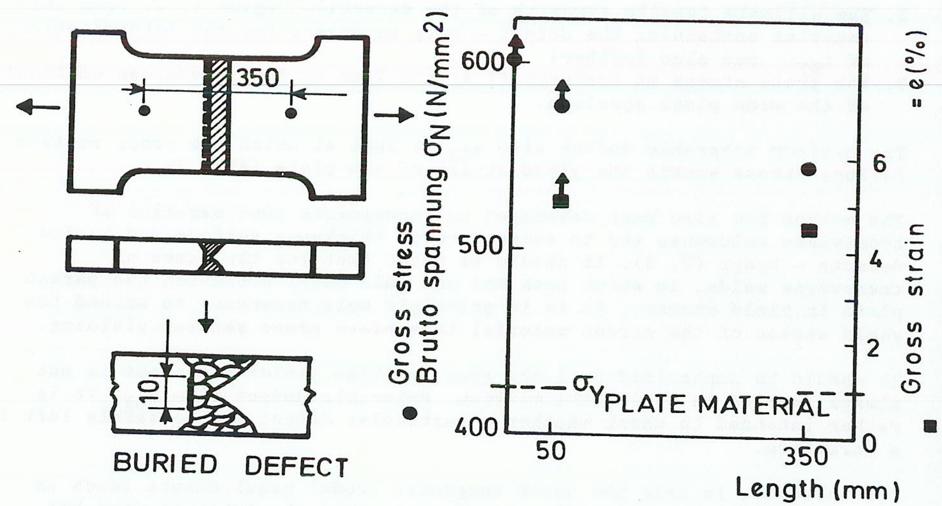

Fig. 4 Measured gross stress and gross strain of weldment with an embedded defect.

The test results, depicted in Figure 4, show that gross section yielding occurred irrespective of defect dimensions. It is remarkable to see that a buried defect with a section equalling one third of the plate section failed at 5% gross strain. In order to assist in evaluating the deformation mode, a selection of moiré pictures is given in Figures 5a and 5b. The interference patterns confirms that gross section yielding occurred. The moiré fringes in the unnotched part of the specimen are clearly visible. From the high density of moiré lines viewed from Figure 5a, the buried defect of 10mm x 50mm can be located.

FINAL OBSERVATIONS - CONCLUSIONS

An outline has been given of the applicability of wide plate testing for the assessment of the significance of defects on failure behaviour. The wide plate test results were assessed using the Gross Section Yielding concept. This concept aims to define a maximum tolerable defect size a_{gy} for gross section yielding before fracture ensues. These maximum tolerable dimensions enables the definition of acceptable defects. Defects smaller than a_{gy} are considered to be acceptable, since they tolerate a strength of at least yield point magnitude and a sufficient overall ductility.

The gross section yielding concept must be considered as a direct fitness for purpose approach. This concept, which gives an adequate margin of safety in terms of overall deformation, should be considered as either an alternative, or a complementary method that should be used together with defect tolerance calculation methods based on a single crack tip fracture toughness parameter. Wide plate testing is in particular recommended for expensive structures for which conservative defect tolerance levels may prove to be extremely expensive.

Furthermore, the gross section yielding concept permits a realistic assessment of the integrity of those structures that serve an important safety function and that have deliberately been designed not to fail in the elastic range of stress but only under gross overload in the plastic range. In other words, the gross section yielding concept can be considered as an important piece of the jigsaw puzzle characterized by the presently adopted procedures of analysis in fracture mechanics.

In the author's experience, larger defects can be tolerated than those predicted by the traditional fitness for purpose approaches, despite the stringent requirement of gross section yielding. This observation applies especially for notch tough materials which contain either surface or buried defects. Moreover, the size of defect used in wide plate testing giving rize to gross section yielding, are normally found to be so large that they can be reliably detected using the convensional NDT techniques.

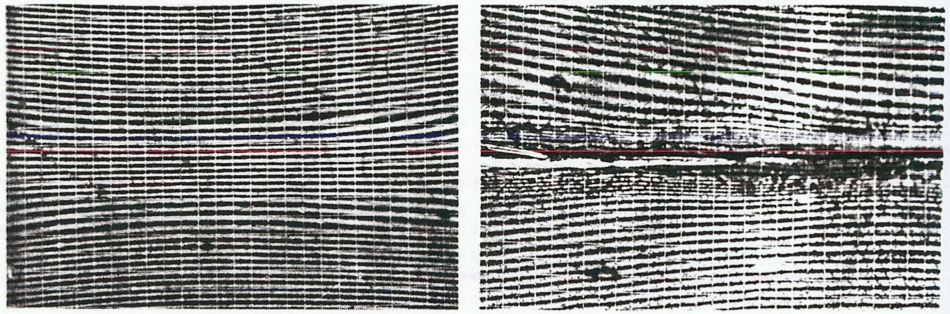

Fig. 5 Moiré pictures of weldments with a buried defect.
a) 10 mm x 50 mm b) 10 mm x 350 mm

SYMBOLS USED

a_{gy} =Value of a, demarcating Gross section/Net section yielding.

GCOD =Gent Crack Opening Displacement (Gauge length : 8 mm).

GSY. =Gross section yield (i.e. gross stress > yield stress).

NSY. =Net section yield (i.e. gross stress < yield stress).

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