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Assessment of notched Polyvinyl chloride (PVC) tubular beams using the Theory of Critical Distances and Finite Element analysis

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Abstract

This paper combines the Theory of Critical Distances (TCD) and Finite Element Analysis (FEA) to provide estimations of fracture loads in Polyvinyl chloride (PVC) tubular beams containing notch-type defects. The methodology is, however, theoretically applicable to any kind of material and component developing a predominant linear-elastic behavior. FEA is used to determine the stress field at the notch tip, which is then combined with one of the TCD failure criteria (the Point Method, PM) to derive the corresponding critical load. The results prove that this methodology provides reasonable predictions of fracture loads.

Keywords: critical load; fracture; tubular cantilever beam; U-notch; theory of critical distances; FEA

1. Introduction

The use of polymers in load-bearing applications has increased rapidly in the last decades. Some examples can be found in pressure vessels and pipelines, where these materials take advantage of properties such as low cost, long-term durability against the aggressive environment, or high strength-to-weight ratio, in comparison with other materials (EL-Bagory et al., 2015; EL-Bagory and Younan, 2017). In this context, the development and validation of appropriate methodologies for the prevention of failure of polymeric components have become crucially important.

Structural integrity methodologies are used to assess defects in engineering structures (BS7910, 2019; R6, 2015; Kocak et al., 2008). These approaches traditionally assume that defects are infinitely sharp (i.e., cracks) and combine fracture mechanics (Anderson, 2005; Broek, 2012) and plastic collapse analyses to provide estimations of critical loads or critical defects. Nevertheless, the reality in many structural components reveals that defects are not necessarily sharp, and may have a finite radius on their tip. Treating such defects as if they were cracks would provide over-conservative assessments in many situations. These types of defects (often called notches) generate less aggressive stress fields and lower constraint conditions that allow the corresponding plastic zone to be larger than that developed in cracked conditions. Therefore, finally, this notch effect involves an increase of the fracture resistance of the material, which in notched conditions is generally referred to as the apparent fracture

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toughness (K^N_{mat}). As a result, it is necessary to provide structural integrity evaluation methods that are able to take into account the notch effect and to accurately predict the critical loads developed in notched conditions.

When conducting notch assessments, there are two main types of criteria: the global fracture criterion, based on the idea that in the critical situation, the notch stress intensity factor (K_p) reaches a critical value (K^c_p), as established in equation (1), and local criteria, based on the study of the stress or strain fields around the notch tip.

$$K_p = K_p^c \tag{1}$$

Among the latter, the Theory of Critical Distances (TDC) stands out and been successfully applied to a wide variety of failure mechanisms (e.g. fatigue (Taylor, 2007), fracture (Cicero et al., 2012; Madrazo et al., 2012), stress corrosion cracking (González et al., 2019)) and materials.

The TDC is comprised of a group of methodologies originally proposed by Neuber (1936) and Peterson (1959) that may be used to predict the fracture and fatigue behaviour of structural components containing notches. All these methodologies use two additional material parameters: a material length parameter named the critical distance (L), and a material strength parameter named the inherent strength (σ_o). In fracture analysis, these two parameters are directly related to the material fracture resistance (K_{mat}) through equation (2):

$$L = \frac{1}{\pi}\left(\frac{K_{mat}}{\sigma_o}\right)^2 \tag{2}$$

When the material behaviour is entirely linear elastic, the inherent strength may be assumed to be equal to the material ultimate tensile strength (σ_u). Otherwise, σ_0 tends to be higher than σ_u, and as long as plasticity is generated in the vicinity of the notch, this trend becomes more obvious. In such a case, σ_0 must be determined (calibrated) by experimental testing of samples containing notches of different radii, or by combining experimental testing with a stress analysis (e.g. finite element (FE) modelling) (Taylor, 2007).

Within the different methods belonging to the TCD, the point method (PM) is distinguished by its simplicity and its capacity to provide similar accuracy in fracture predictions than other TCD methods, such as the line method, the area method, or the volume method (Taylor, 2007). According to the PM, fracture will occur when the stress at a distance of L/2 from the notch tip is equal to the inherent strength σ_0. The mathematical expression is given by equation (3):

$$\sigma\left(\frac{L}{2}\right) = \sigma_o \tag{3}$$

Therefore, the PM can analyse the fracture behaviour of notched components simply by knowing L, σ_0 and the linear elastic stress field at the tip of the notch. The development of finite element tools has made it easier to determine the stress distribution generated by stress risers, which has enabled the TCD methodology to be extensively validated (Taylor, 2007). However, this validation has been focused on fracture mechanics notched samples (e.g., CT and SENB notched samples), and not on structural components. With this background, the present paper attempts to verify the application of TDC (combined with FEA) in large polymer structural components, specifically, in PVC tubular cantilever beams with U-notches. The approach is analogous to that performed by the authors on Al6060-T66 tubular beams (Sánchez et al., 2020), in which the combination of the TCD and FEA provided accurate predictions of fracture loads in a metallic material.

This being said, Section 2 introduces the material employed and describes the experimental and analytical procedures. Section 3 collects the experimental results, presents the load-bearing capacity predictions and analyses the results. Finally, Section 4 gathers the main conclusions.

2. Materials and Methods

2.1. Materials

In the development of this work, polyvinyl chloride (PVC) has been selected. PVC is one of the most widely used amorphous thermoplastics. It can be found in two different forms: plasticized PVC (flexible PVC) or un-plasticized PVC (rigid PVC), the second one being the most suitable form in structural applications due to its stiffness and strength, and thus the one chosen in this study.

In order to conduct the validation of the proposed assessment methodology, four PVC cantilever beams were utilized. The nominal length of the beams was 1.8 m in all cases, and two different geometries were employed: one with an outer diameter of Ø315 mm and thickness of 6.8 mm, and another one with an outer diameter of 200 mm and thickness of 3.7 mm. The beams were fabricated following the Spanish standard UNE-EN 1401 (2009).

2.2. Methods

In structural integrity analyses, a key step consists in the characterization the material mechanical properties. This characterisation was performed from material extracted from one of the beams (Ø315 mm, 6.8 mm thick), which was used for cutting and machining both tensile and fracture mechanics specimens. The remaining three tubes were used for the structural validation tests.

The mechanical properties of the PVC were determined according to ASTM D638 (2014). Three specimens were obtained along the longitudinal axis of the beam. The main dimensions of the specimens are shown in Fig. 1. Tensile tests were performed at room temperature with a crosshead speed of 5 mm/min.

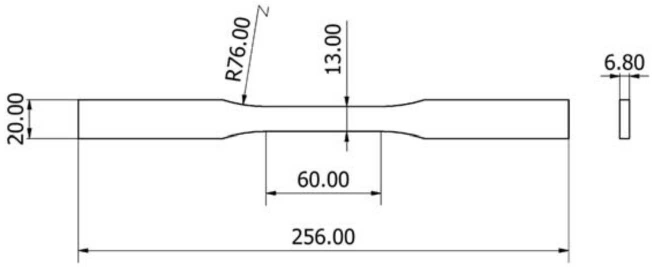

Fig. 1. Geometry of the tensile samples. Dimensions in mm.

The fracture behaviour of PVC under mode I loading was determined following the standard ASTM D5045 (2014). The specimen configuration selected was the single edge notched bend (SENB), obtained from the tube in LC orientation to simulate the defect propagation direction occurring in the validation tubes. The geometrical parameters of the samples are shown in Fig. 2. It can be observed that the thickness is slightly smaller than that of the tube since the sample must be prismatic. In this study, three different notches have been considered: 0 mm (crack-type defect), 1 mm, and 2 mm. Fracture tests were carried out at room temperature with a crosshead speed of 10 mm/min.

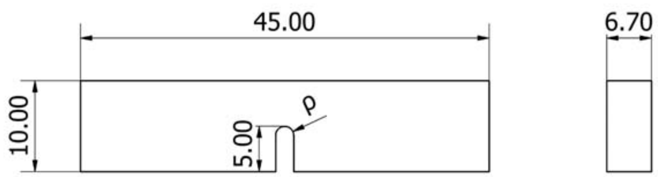

Fig. 2. Geometry of SENB fracture specimens. Dimensions in mm.

To complete the experimental program, the three validation cantilever beams were prepared for their testing. The U-notch type defects were machined at a distance of 350 mm from one of the final edges. All the machined defects were through thickness circumferential notches. To generate a fixed support, the tubes were introduced into a block of reinforced concrete, as shown schematically in Fig. 3. The geometry of each tube and its corresponding defect are gathered in Table 1.

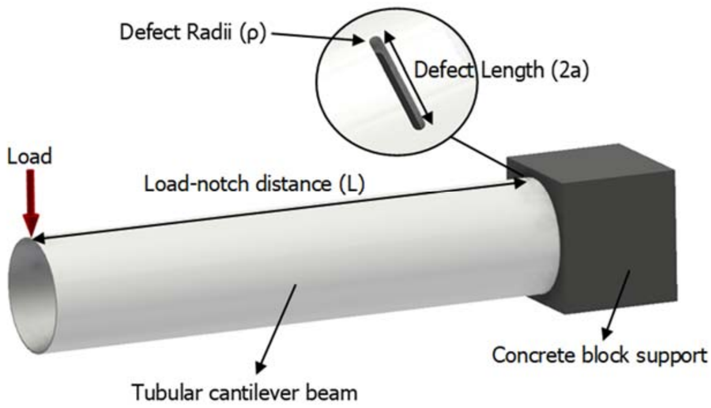

Fig. 3. Scheme of the PVC tubular beams containing U-Notch through thickness circumferential notches.

Table 1. Geometrical parameters of the tubes and their corresponding U-notch: Ø, outer diameter; B, tube thickness; D, distance from concrete support to notch; L, beam length; 2a, defect length; ρ, defect radius. Dimensions in mm.

Tube	Ø	B	D	L	2a	ρ
PVC1	315	6.8	28.0	1415	27.4	1.5
PVC2	200	3.7	19.4	1466	17.4	0.8
PVC3	200	3.7	24.4	1462	34.8	0.8

The bending test of the tubes was performed on a test bench, fixing the concrete block with screws, as seen in Fig. 4. In the free edge, a single load was applied at a rate of 10 mm/min while the vertical displacement was measured by a laser comparator. Additional details about the whole experimental program may be found in (Cicero et al., 2021), where the test results were previously employed with a different target (analysis by using Failure Assessment Diagrams).

Fig. 4. Experimental setup of the tubular beams.

The present work provides a methodology for the determination of load-bearing capacity in tubular cantilever beams including U-Notch type defects by applying the TDC approach together with an FEA. As explained above, the TDC requires the stress field on the notch tip to be defined. In this sense, a set of FEA was performed in linear elastic conditions both for fracture specimens and for tubular beams, employing the finite element software ANSYS 19.2 (Ansys Inc, Canonsburg, PA, USA).

In order to calibrate the TCD parameters, half of the SENB fracture specimens were reproduced with a 3D model (due to symmetry conditions), using a structured mesh formed by 20-node hexahedral elements, as seen in Fig. 5 (a). The analysis could have been performed on a quarter of the specimens, but the computational effort on half of the specimen was sufficiently moderate for our purposes. Besides, a refined mesh (see Fig. 5 (b)) around the notch tip was defined to capture accurately the high stress gradient generated in this region, the minimum size being around 0.003 mm (after a sensibility analysis). Around 111,100 elements were utilised in each FE model.

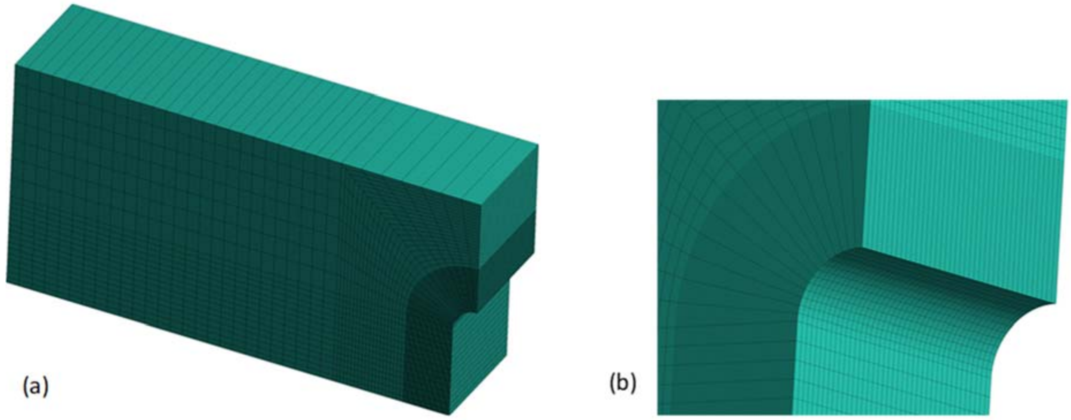

Fig. 5. Mesh and geometry of the FE model of the SENB specimens (a); detail at the notch tip (b).

In order to determine the maximum principal stress through the middle line of the fracture plane, a path was created from the front of the notch root to the end of the specimen. Once the stress distribution at failure had been obtained for each notch radius, the critical distance L (and σ_o) was calculated by applying the PM. Following this approach, the different curves cross each other at a single point whose coordinates correspond to L/2 and σ_o, as shown in Fig. 6.

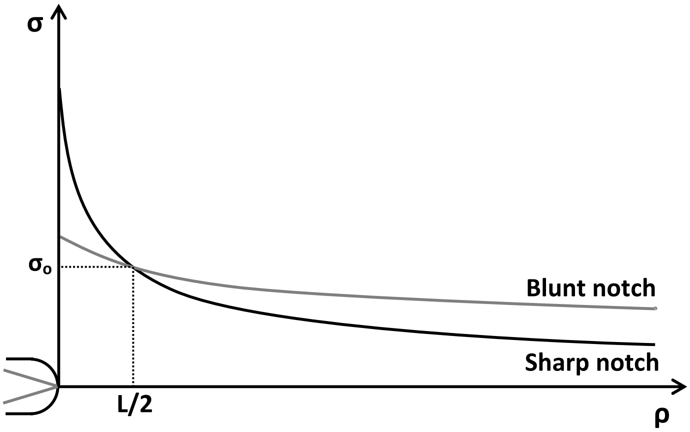

Fig. 6. Derivation of the TDC parameters when applying the PM approach.

Finally, and taking advantage of their symmetry, only a half of the three cantilever beams were modeled with the following constraints: fixed support in the part of the tube where the concrete block was placed, and a displacement restriction of the nodes in the symmetry plane in the perpendicular direction to this plane. Then, a single load was applied at the free edge of each tube. The model was partitioned creating a structured mesh and with 20-node hexahedral elements, as shown in Fig. 7 (a). Moreover, the area surrounding the notch tip was refined with an element size of 0.006 mm. The stress profiles were obtained in pre-defined paths (see Fig. 7 (b)) along the circumferential direction, in the middle of the tube thickness and starting on the notch tip. With all this, the load-bearing capacity (or critical load) of each tube could be easily estimated as the load that fulfilled the PM failure criterion (equation (3)).

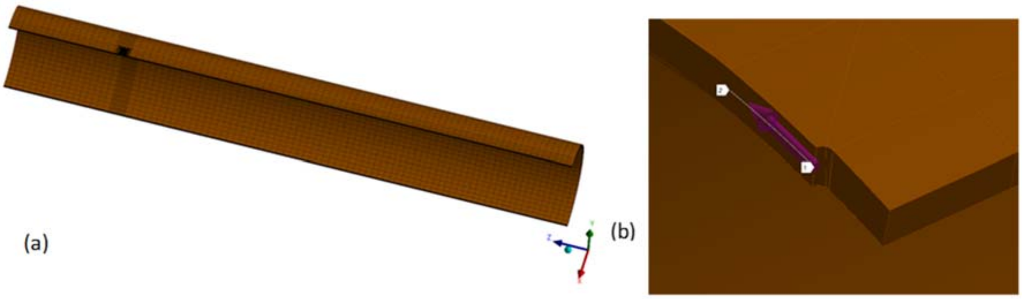

Fig. 7. Example of the FE model of the tubular beams (a) and detail of the defined paths (b).

3. Results

3.1. Experimental results

Table 2 gathers the average results of the tensile properties, together with the resulting standard deviation.

Table 2. Tensile parameters of PVC (mean and standard deviation): E, modulus of elasticity; $\sigma_{0.2}$, proof strength; σ_u, ultimate tensile strength; ε_u, elongation under maximum load.

E (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
3471.5 ± 199.6	38.6 ± 1.5	51.13 ± 1.1	41.11 ± 11

Concerning the fracture tests, some examples of the obtained load-displacement curves are shown in Fig. 8.

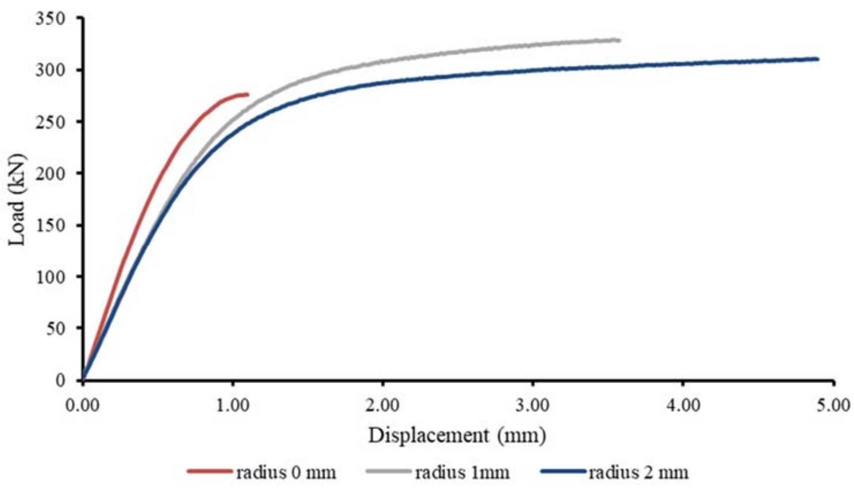

Fig. 8. Examples of load-displacement curves of the fracture tests.

The critical loads of each SENB fracture sample, as well as the resulting apparent fracture toughness, K^N_{mat}, are shown in Table 3. At this point, a clear notch effect can be noticed, with significant increases of the apparent fracture toughness when the notch radius becomes larger. The upper limit of the fracture resistance from which the material is operating beyond plane stress conditions (i.e., plane stress onset) was calculated to verify the uniformity of the fracture conditions for the different notch radii. Equation (4) provides a criterion in this regard (Taylor, 2007), for this material 5.6 MPa·m$^{1/2}$:

$$K_{\text{Plane stress}} = \sigma_Y(\pi B)^{1/2} \quad (4)$$

Thus, both the fracture samples and the validation beams were tested under full plane stress conditions.

Table 3. Experimental results obtained from SENB samples.

Specimen	ρ (mm)	Defect length (mm)	Critical Load (N)	K^N_{mat} (MPa·m$^{1/2}$)
0-1	0	4.63	238.08	6.41
0-2		4.30	276.33	6.46
0-3		4.46	290.19	7.64
1-1	1	5.00	325.00	13.83
1-2		5.00	328.60	14.96
1-3		5.00	343.00	15.92
2-1	2	5.00	311.40	17.73
2-2		5.00	318.00	17.58
2-3		5.00	324.70	17.89

The experimental curves obtained in the validation tubes are represented in Fig. 9, while the results of experimental load-bearing capacity are presented in Table 4.

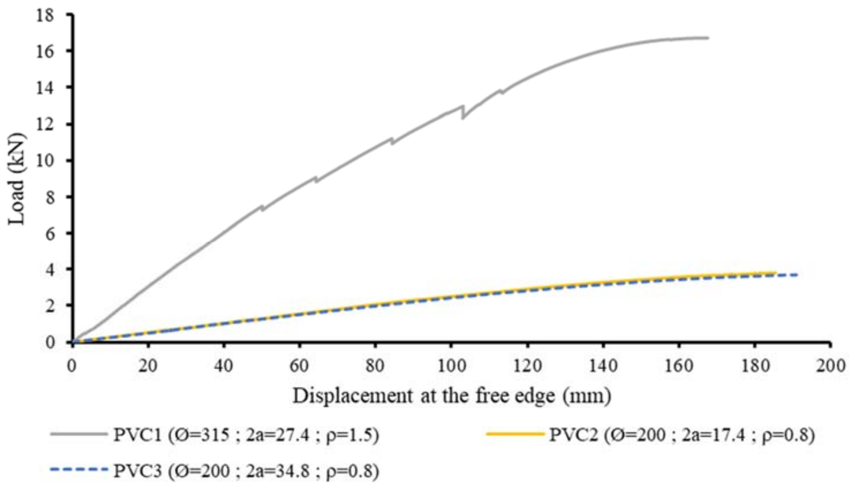

Fig. 9. Load-displacement curves of the different tubular beams. The dimension of tube and defect in mm.

3.2. Load-bearing capacity predictions

The stress-distance curves of the SENB specimens (average values for each notch radius) are shown in Fig. 10. Even though the stress profiles should theoretically cut off in a single point, this does not normally occur when the available data is limited. Thus, the TDC material parameters have been calculated as the mean of the different cut-offs, the main statement of the PM being reasonably fulfilled. The result is L=0.14 mm and σ_o=185 MPa.

Likewise, the stress-distance curves of the structural components are shown in Fig. 11, for a single load of 1N at the free edge. In order to determine the critical loads, and provided that the process is linear-elastic, it is necessary only to scale the curves in Fig.11 until the PM fracture condition is achieved. The results are gathered in Table 4.

Fig. 12 compares the experimental results with the corresponding estimations, showing acceptable predictions of the load-bearing capacity. The entire set of values obtained fall within a reasonable deviation of ±20%, a well-known criterion generally accepted in fracture research (Berto and Lazzarin, 2014; Cicero et al., 2015, 2013; Taylor, 2007). It can be observed that the predictions tend to overestimate the LBC on average by +5.5%, the highest deviation being of around +19.6%. Here it should be noted that this methodology includes no safety factors, as it is usual in structural integrity assessments. Moreover, the maximum deviation (+19.6%) was observed in the beam with the most obvious non-linear behaviour (PVC1, see Fig. 9), and then further from the theoretical linear-elastic nature of the TCD, which may be more difficult to compensate through the calibration process of the material critical distance.

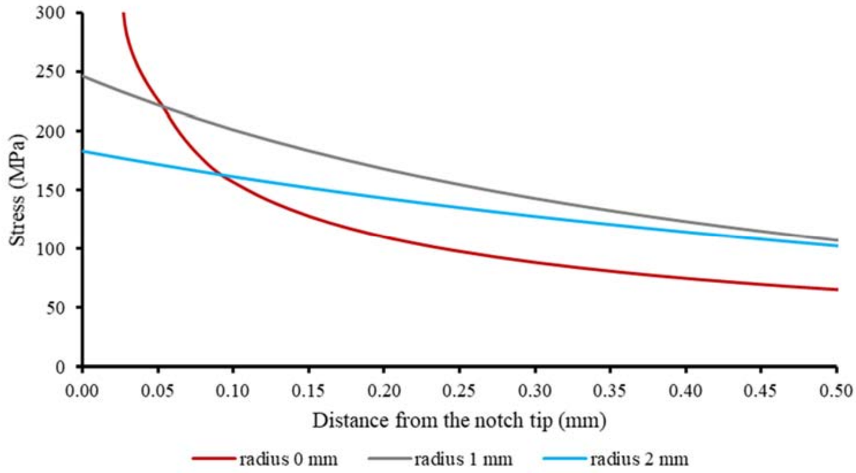

Fig. 10. Stress-distance curves at critical load in SENB fracture specimens.

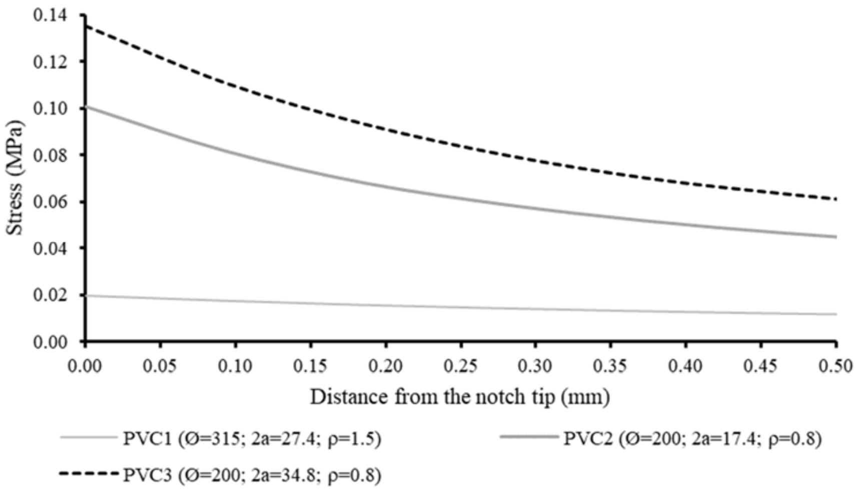

Fig. 11. Stress-distance curves in tubular beams obtained by applying a unit load (1N).

Table 4. TDC parameters obtained from calibration, together with the experimental and the estimated values of load-bearing capacity.

Tube	L (mm)	σ_o (MPa)	LBC_{est} (kN)	LBC_{exp} (kN)
PVC1			20.00	16.72
PVC2	0.14	185	4.20	3.80
PVC3			3.19	3.70

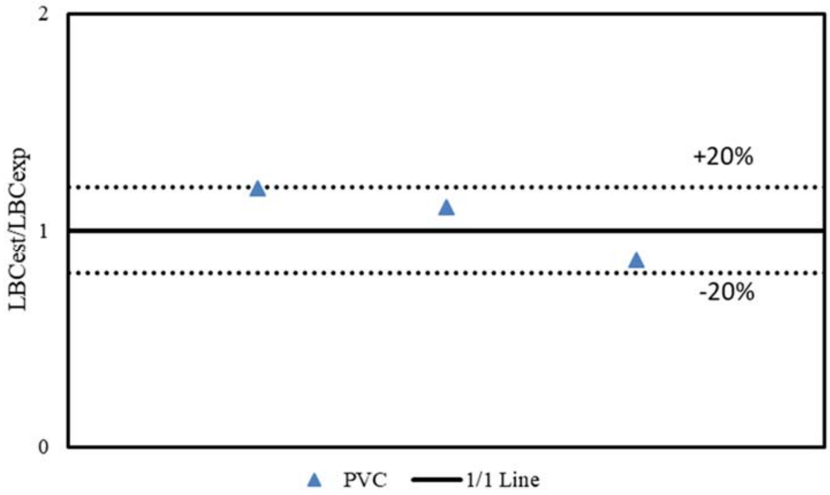

Fig. 12. Comparison between LBC experimental results and LBC estimated values.

4. Conclusions

In this article, a methodology for estimating the critical load in tubular beams containing U-notches has been verified. This method is based on the application of the Theory of Critical Distances (TCD), through the point method (PM), and finite element (FE) linear elastic simulations.

The method has been validated on three PVC cantilever beams, which have circumferential through-thickness U-notches. Tensile and fracture tests were performed to determine the mechanical properties of the material, and the combination of the fracture tests on notched SENB specimen and the finite element analyses allowed the critical distance and the inherent strength of the material to be calibrated. Finally, finite element simulations of the cantilever beams were performed to determine the estimated value of the critical loads, which are those loads that meet the PM criterion.

The predicted critical loads represent acceptable estimations of the experimental critical loads, always within the typical acceptable scatter band of the fracture process (±20%), and with an average overestimation of +5.5% (without using any safety factor).

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References

Anderson, T.L., 2005. Fracture mechanics: fundamentals and applications. CRC press, Boca Raton, FL.

ASTM D5045, 2014. Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials. ASTM International, West Conshohocken, PA.

ASTM D638-14, 2014. Standard Test Method for Tensile Properties of Plastics. ASTM International, West Conshohocken, PA.

Berto, F., Lazzarin, P., 2014. Recent developments in brittle and quasi-brittle failure assessment of engineering materials by means of local approaches. Mater. Sci. Eng. R Reports 75, 1–48.

Broek, D., 2012. Elementary engineering fracture mechanics, 4th ed. Martinus Nijhoff, Dordrecht, The Netherlands.

BS7910, 2019. Guide to methods for assessing the acceptability of flaws in metallic structures. British Standards Institution, London.

Cicero, S., Madrazo, V., Carrascal, I.A., 2012. Analysis of notch effect in PMMA using the Theory of Critical Distances. Eng. Fract. Mech. 86, 56–72. https://doi.org/10.1016/j.engfracmech.2012.02.015

Cicero, S., Madrazo, V., García, T., 2015. On the assessment of U-shaped notches using Failure Assessment Diagrams and the Line Method: experimental overview and validation. Theor. Appl. Fract. Mech. 80, 235–241.

Cicero, S., Madrazo, V., García, T., Cuervo, J., Ruiz, E., 2013. On the notch effect in load bearing capacity, apparent fracture toughness and fracture mechanisms of polymer PMMA, aluminium alloy Al7075-T651 and structural steels S275JR and S355J2. Eng. Fail. Anal. 29, 108–121.

Cicero, S., Sánchez, M., Arroyo, B., Fuentes, J.D., Álvarez, J.A., 2021. Estimation of the load-bearing capacity of tubular cantilever beams containing through-thickness circumferential U-notches. Eng. Struct. 229. https://doi.org/10.1016/j.engstruct.2020.111598

EL-Bagory, T.M.A.A., Sallam, H.E.M., Younan, M.Y.A., 2015. Evaluation of fracture toughness behavior of polyethylene pipe materials. J. Press. Vessel

Technol. Trans. ASME 137, 1–10. https://doi.org/10.1115/1.4029925
EL-Bagory, T.M.A.A., Younan, M.Y.A., 2017. Crack Growth Behavior of Pipes Made from Polyvinyl Chloride Pipe Material. J. Press. Vessel Technol. Trans. ASME 139, 1–17. https://doi.org/10.1115/1.4033124
R6: assessment of the integrity of structures containing defects, Rev. 4, 2015. EDF Energy, Gloucester, UK.
González, P., Cicero, S., Arroyo, B., Álvarez, J.A., 2019. A Theory of Critical Distances based methodology for the analysis of environmentally assisted cracking in steels. Eng. Fract. Mech. 214, 134–148.
Kocak, M., Webster, S., Janosch, J.J., Ainsworth, R.A., Koers, R., 2008. FITNET Fitness-for-Service (FFS) Procedure, Revision MK8. GKSS, Hamburg, Germany.
Madrazo, V., Cicero, S., Carrascal, I.A., 2012. On the Point Method and the Line Method notch effect predictions in Al7075-T651. Eng. Fract. Mech. 79, 363–379. https://doi.org/10.1016/j.engfracmech.2011.11.017
Neuber, H., 1936. Theorie der technischen Formzahl. Forsch. auf dem Gebiet des Ingenieurwesens A 7, 271–274.
Peterson, R.E., 1959. Notch Sensitivity, Metal Fatigue, G. Sines, J. Lwaisman. New York McGrawrHill.
Sánchez, M., Cicero, S., Arroyo, B., Álvarez, J.A., 2020. Coupling finite element analysis and the theory of critical distances to estimate critical loads in al6060-t66 tubular beams containing notches. Metals (Basel). 10, 1–11. https://doi.org/10.3390/met10101395
Taylor, D., 2007. The theory of critical distances: a new perspective in fracture mechanics. Elsevier, London.
UNE-EN 1401, 2009. Plastics piping systems for water supply and for buried and above-ground drainage and sewerage under pressure - Unplasticized poly(vinyl chloride) (PVC-U). European Committee for Standardization, Brussels.