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ANALYSIS OF P-SPT SPECIMENS USING DAMAGE MECHANICS MODEL TO ASSESS CRACK LENGTH AT PEAK LOAD

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ABSTRACT

Pre-cracked small punch tests (known as p-SPT) are used to assess fracture properties of aged nuclear materials in cases of limited availability of materials which is insufficient to conduct conventional standard tests. In this paper, the Gurson-Tvergaard-Needleman (GTN) model is used to compute crack growth at peak loads for material 20MnMoNi55 by analysing pre-cracked small punch test specimens of initial crack length 4.0, 4.5, and 5.0 mm. Size of the p-SPT specimen is 10 x 10 x 0.5 mm. Crack tip radius is 0.1 mm. A parametric study is carried out to assess the effect of variation of GTN material parameters on load v/s punch displacement data. The next task is to determine GTN parameters, which can compute load v/s displacement data close to experimental values. It may be observed that during simulation, there is a noticeable amount of crack growth at peak loads in all p-SPT specimens. These crack growth data are calculated and used to obtain exact crack length data at peak loads. The relation between crack length and peak load is determined and compared with empirical correlation reported in the literature.

1 INTRODUCTION

Taslim D. Shikalgar et al. (2018) compared numerically computed load versus punch displacement data by elastic-plastic FE analysis with the experimental data of p-SPT specimens. There was a significant difference in peak loads between measured and computed values. It was presumed that the difference between these two results was due to some extent of crack growth in pre-cracked specimens during experiments before the onset of peak loads. To estimate crack growth data at peak loads, a series of FE (elastic-plastic) simulations of p-SPT specimens was carried out for different initial crack lengths. The crack length for which computed peak load matched with the experimental peak load, has been assumed to be the actual crack length during experiment at peak load. This helped to determine a correlation between peak load with the crack length in p-SPT specimen. Figure 1 shows this plot along with an empirical correlation for material 20MnMoNi55. However, it is desirable to proof this presumption by an alternative method.

In this work, the Gurson-Tvergaard-Needleman (GTN) model is used to compute crack growth at peak loads for material 20MnMoNi55 by analysing pre-cracked small punch test specimens of initial crack length 4.0, 4.5, and 5.0 mm. Size of the p-SPT specimen is 10 x 10 x 0.5 mm. A parametric study is carried out to assess the effect of variation of GTN material parameters on load v/s punch displacement data. The next task is to determine GTN parameters, which can compute load v/s displacement data close to experimental values. It may be observed that during simulation, there is a noticeable amount of crack growth at peak loads in all p-SPT specimens. These crack growth data are computed and used to get exact

crack length data at peak loads. The relation between crack lengths and peak load is determined and compared with the empirical correlation reported earlier. The methodology described in this paper confirming presumption reported in Taslim D. Shikalgar et al. (2018)

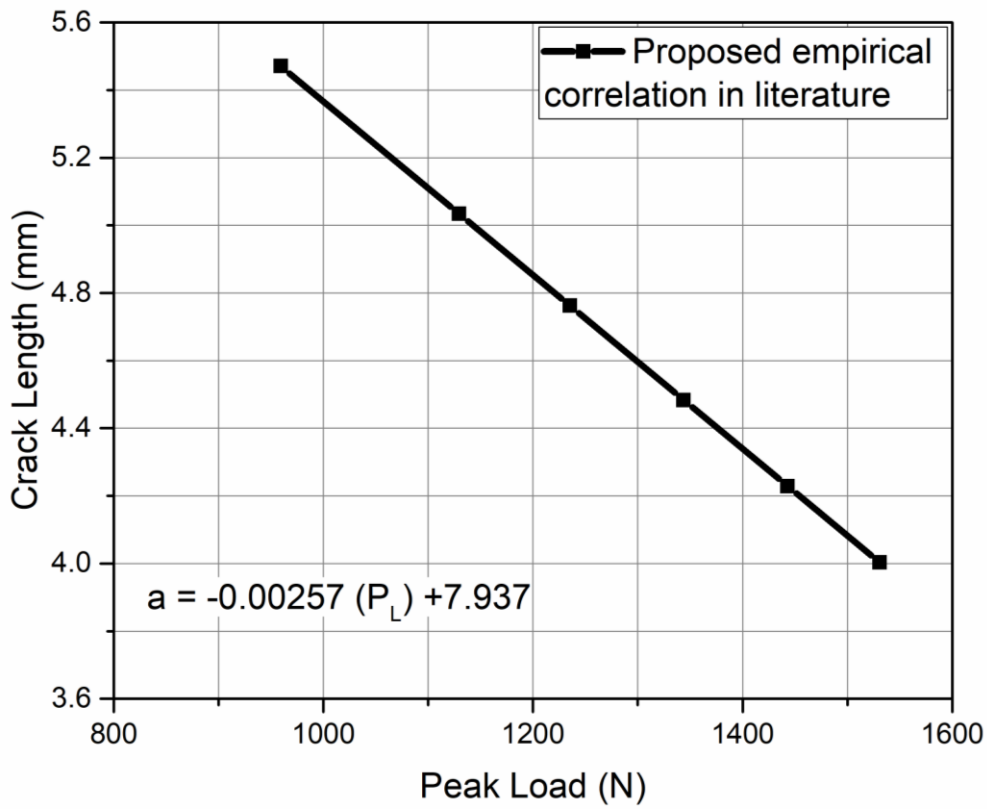

Figure 1. Crack length v/s numerically computed peak load data (Taslim D. Shikalgar et al. (2018))

2 FE ANALYSIS OF P-SPT SPECIMENS USING GTN MATERIAL MODEL

2.1 Modeling

The pre-cracked small punch test specimens of initial crack length 4.0, 4.5 and 5.0 mm are simulated using BARC in-house finite element implicit code MADAM (MAterial DAmage Modeling) (BARC technical report. In House Finite Element Code MADAM (MAterial DAmage Modeling), 1999). This code has ability to solve two and three-dimensional finite element models. The Gurson-Tvergaard-Needleman material model is also available in this code. The propagation of crack is traced by counting the damaged gauss points along crack-line. A gauss point is assumed to be damaged entirely when its void volume becomes void volume fraction at fracture (f_f). The crack growth is determined by calculating maximum distance between crack tip and damaged gauss points lying along the crack line.

In this present work, the p-SPT specimen is analysed using FE three-dimensional model. Due to the symmetry of the specimen geometry and loading conditions, only one-half of the pre-cracked specimen is modelled using 8-node fully integrated iso-parametric 59626 brick elements. Mesh is refined near the crack, where the minimum length of the brick element is equal to 35.7 μm along the direction of the length of the crack as well as in thickness direction. The lower die, upper die, and punch are modelled as rigid bodies. The multi-body dynamic concept is used to model the progress of contact between the specimen and die with associated friction between the two surfaces. The coefficient of friction was taken as 0.1, as suggested by T. E. Garcia (2015) and E. Martinez-Paneda (2016). The displacement controlled

loading is applied on the rigid punch. Figure 2 shows the FE mesh of the specimen and refined mesh near the crack tip of the specimen.

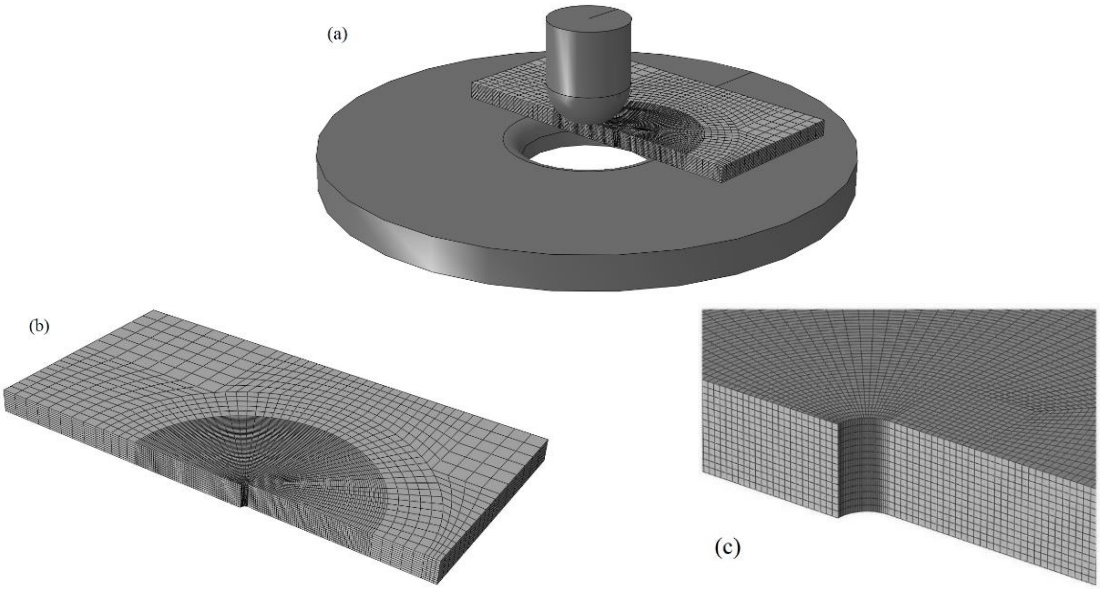

Figure 2. FE model of p-SPT (a) General scheme (the upper die is not shown) (b) FE mesh (c) refined mesh near the crack tip

2.2 Material

The material studied in the present work is 20MnMoNi55. Figure 3 shows the experimentally determined true stress (σ) v/s true plastic strain (ε_p) data and mechanical properties of material 20MnMoNi55.

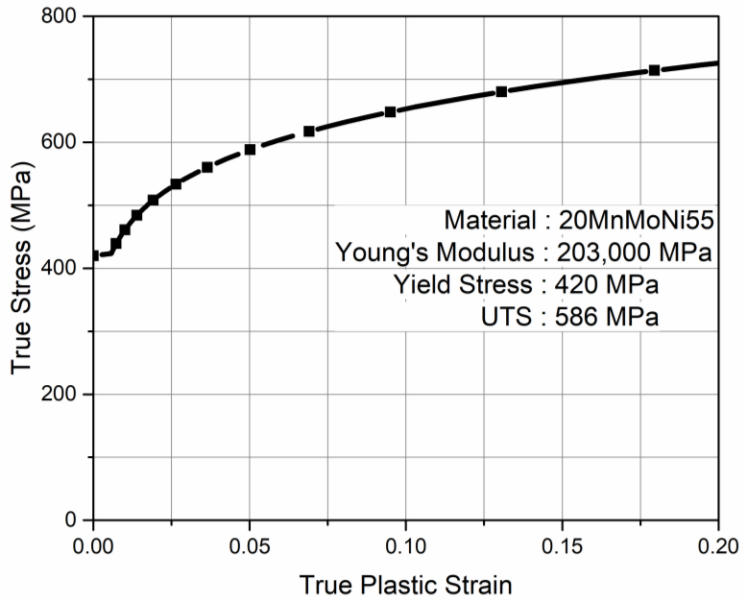

Figure 3. True stress-true plastic strain curve for 20MnMoNi55

2.3 Parametric study by varying GTN material constants

The GTN material model is used to predict the damage of p-SPT specimens. To apply this model, nine material parameters are required. A parametric study of p-SPT specimens of crack length 4.5 mm has been carried to assess GTN parameters. A comparison of numerical results with the experimental data is necessary for this purpose. Parametric studies are carried out to see the effect of void volume fraction at nucleation (f_n), void volume fraction at coalescence (f_c) and void volume fraction at fracture (f_f) on the load v/s punch displacement data of p-SPT specimens. Some GTN parameters, such as, q_1, q_2, q_3, ε_n and S_n are kept constant during parametric study. In addition to this, the value of f_o is assumed to be significantly low for present material. These values are shown below.

Table 1. GTN Parameters kept constants during the present study

q_1	q_2	q_3	ε_n	S_n	f_0
1.5	1.0	2.25	0.3	0.1	1.0^{-5}

2.3.1 Influence of void volume fraction of nucleation (f_n)

The f_n parameter represents the void volume fraction at nucleation. The variation in the value of f_n is studied in the range of (0.005 - 0.010) to see the influence on load v/s displacement data of p-SPT specimens. Figure 4 (a) shows the comparison of numerical data (including elastic-plastic data) with experimental data. It may be observed that the increase in the value of f_n decreases the value of peak stress and sets its early occurrence. However the post peak slopes of all the curves after peak load is approximately constant.

2.3.2 Influence of coalescence void volume fraction (f_c)

The f_c parameter represents the coalescence void volume fraction. The variation in the value of f_c is studied in the range of (0.014 - 0.03) to see the influence on load v/s displacement data of p-SPT specimens. Figure 4 (b) shows the comparison of numerical data (including elastic-plastic data) with the experimental data. It may be observed that the effect of decrease in the value of f_c decreases the peak load with very small amount.

2.3.3 Influence of void volume fraction at fracture (f_f)

The f_f parameter represents the void volume fraction at fracture. The crack initiation and subsequent crack growth occur when void volume fractions at various gauss points along crack line reach the value of f_f, also termed as complete damage. The values of f_f is studied in the range of (0.16 - 0.30) to see the influence on load v/s displacement data of p-SPT specimens. Figure 4 (c) shows the comparison of numerical data (including elastic-plastic data) with experimental data. It may be observed that the decrease in the value of f_f decreases the peak load.

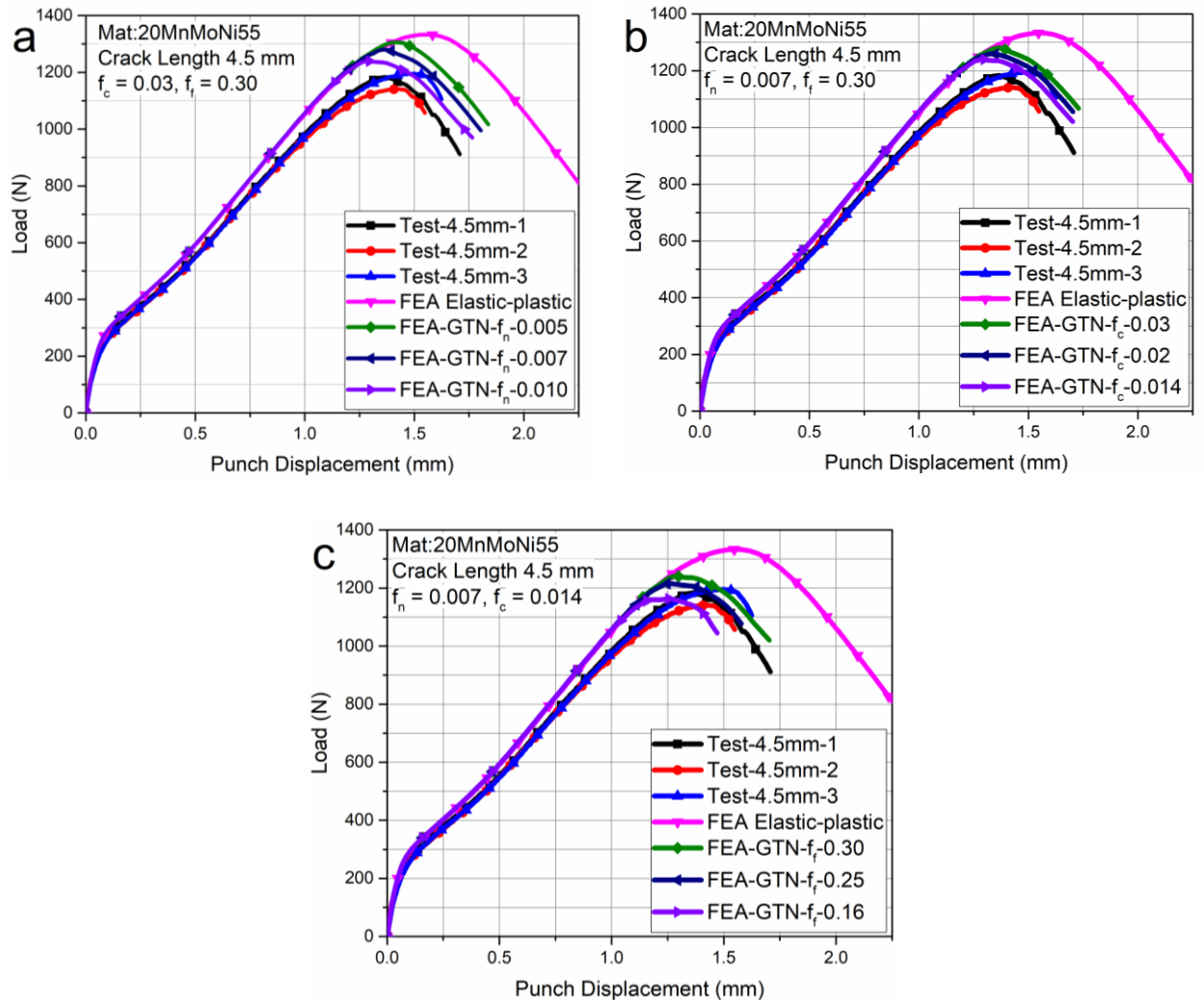

Figure 4. Influence of (a) void volume fraction of nucleation (f_n), (b) coalescence void volume fraction (f_c), and (c) void volume fraction at fracture (f_f) on load v/s displacement data of p-SPT specimens

2.4 Analysis of p-SPT specimens by using finalized GTN material parameters from parametric study

Figure 5 (b) shows computed load-displacement data in comparison to experimental values for 4.5mm crack length for the most optimum set of GTN parameters listed in Table 2. These parameters are then used to carry out FE analysis of p-SPT specimens of crack length 4.0 and 5.0 mm. Figure 5 (a) and (c) show the comparison of numerical data with the experimental data for p-SPT specimens for crack length 4.0mm and 5.0 mm respectively.

Table 2. The best set of GTN Parameters achieved from parametric study for 20MnMoNi55 material

f_n	f_c	f_f
0.007	0.014	0.16

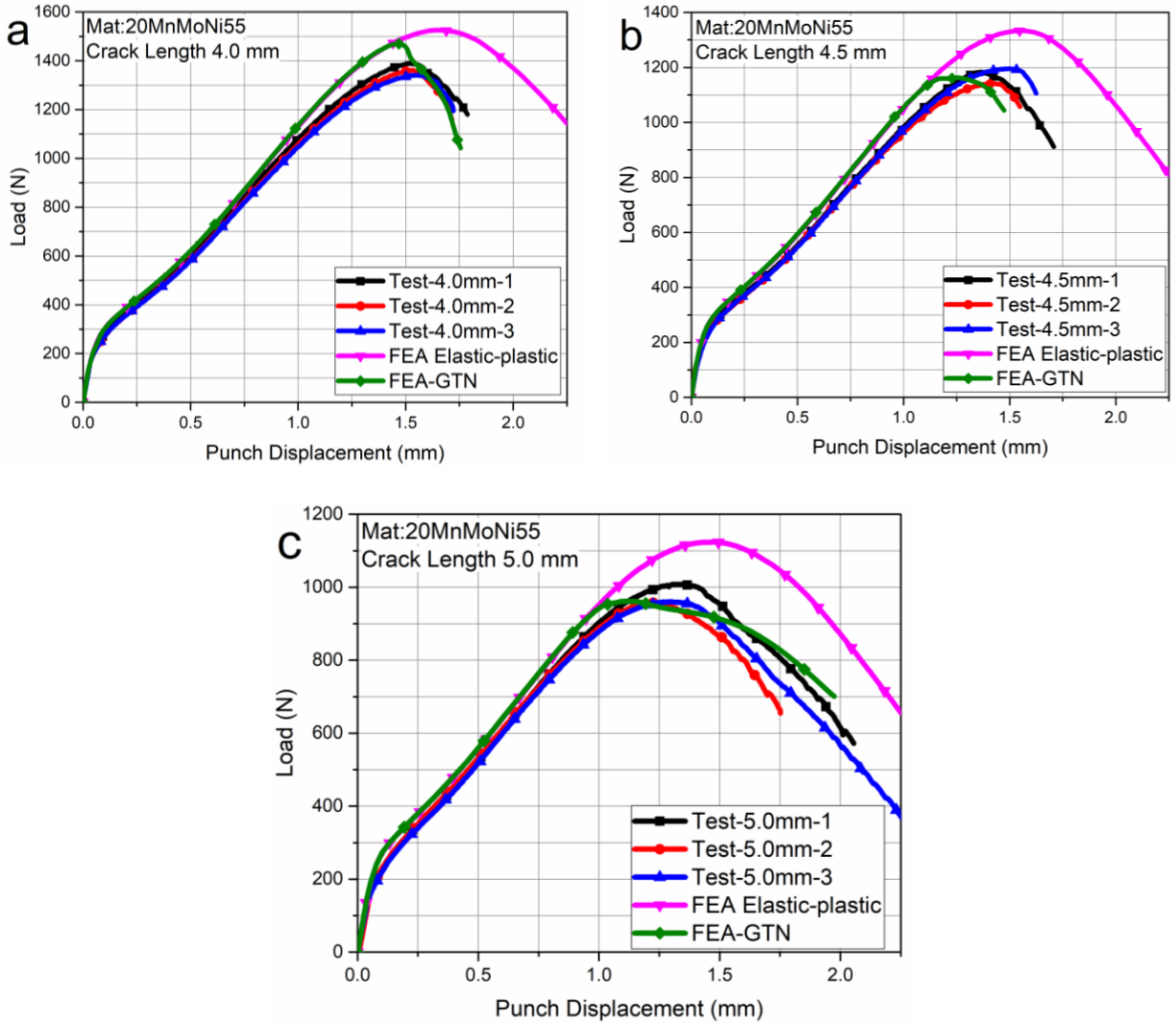

Figure 5. Comparison of FEA GTN, FEA elastic plastic and experimental data

3 ASSESSMENT OF CRACK LENGTH AT PEAK LOAD

The GTN analysis helped to assess the propagation of crack along crack-line. A gauss point is assumed to be damaged completely when its void volume fraction equals to the void volume fraction at fracture (f_f). Each specimen is divided into 14 layers in the thickness direction. Crack growth is measured for each layer at peak load and maximum crack growth in any layer is then taken as final value of crack growth for corresponding specimen. Initial value of crack length is then added to crack growth value to calculate the crack length at peak load. Figure 6 shows the crack growth (elements in blue colour) occurred at peak loads during FE analysis using GTN model. Figure 6 also shows that crack growth in each layer is different. It may be observed that crack growth increases from starting layer 1 (below ball surface) to up to few layers and then decrease up to last layer. Table 3 shows the calculated crack length (including initial crack length) at peak loads.

Table 3. Calculated Crack growth and crack length at peak load from GTN analysis

p-SPT specimen of crack length (mm)	Peak load (N)	Calculated crack growth Δa (mm) at peak loads	Total crack length at peak load (mm)
4.0	1469.74	0.2296	4.2296
4.5	1163.07	0.4506	4.9506
5.0	961.32	0.4091	5.4091

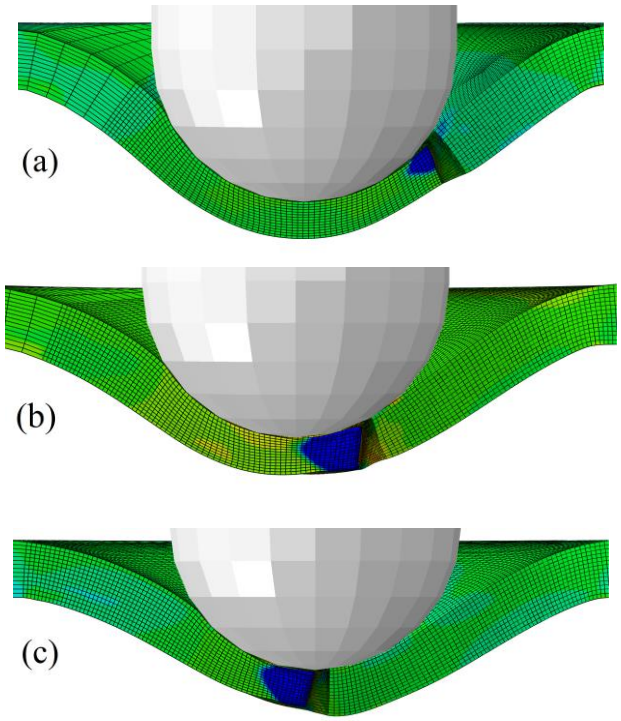

Figure 6. Crack growth at peak load in FE simulations of p-SPT specimen of crack length (a) 4.0, (b) 4.5, and (c) 5.0 mm (upper and lower dies are not shown)

The Figure 7 shows a plot between crack length and peak load using the data from above table. The best-fit linear equation between crack length versus peak load from the present method is shown in Equation (1).

$$a = -0.00232(P_L) + 7.645 \quad (1)$$

The Figure 7 also shows the plot of equation suggested earlier by Taslim D. Shikalgar et al. (2018).

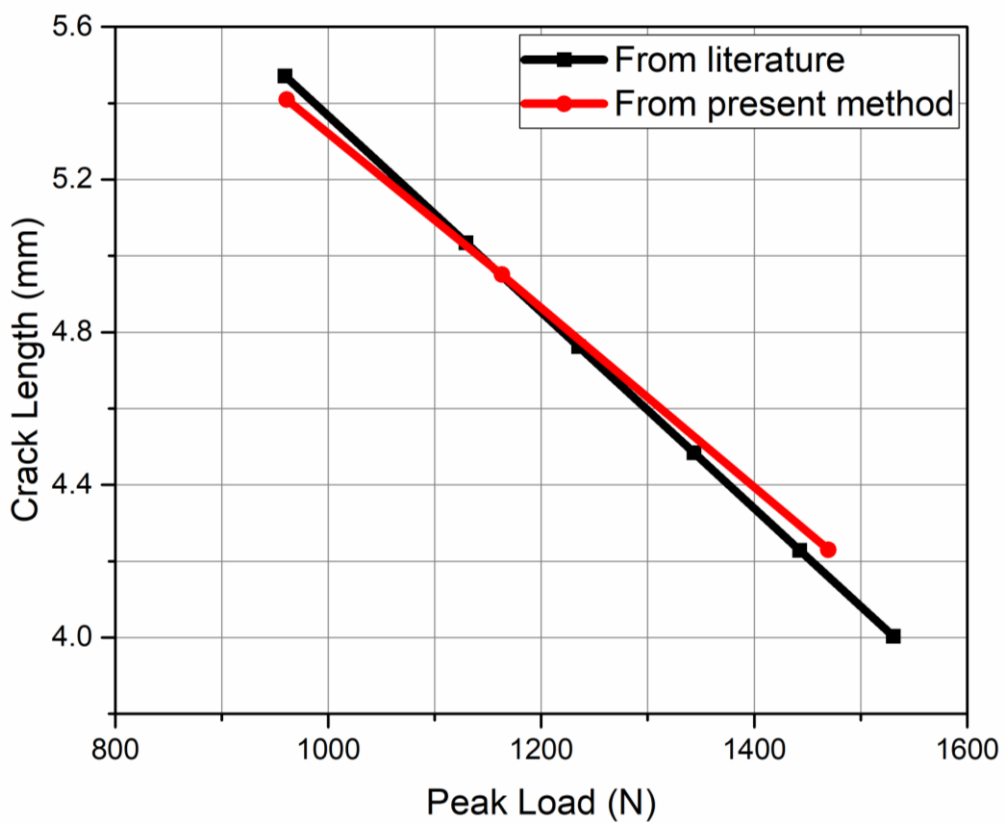

Figure 7. Comparison of crack length v/s peak load data of p-SPT specimens

4 CONCLUSIONS

Following conclusions may be drawn from the present study.

1. There is some extent of crack growth before the onset of peak loads during the testing of p-SPT specimens. The present GTN damage mechanics analysis confirms such phenomena.
2. Computed crack length as a function of peak loads is found to be in reasonable agreement with the data reported in the literature.
3. The methodology described in paper has potential to determine fracture properties of aged nuclear materials using pre-cracked small punch test specimens.

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