

NUMERICAL VERIFICATION OF FRACTURE TOUGHNESS VALUES FOR VERY THIN 3D PRINTED POLYAMIDE SAMPLES

PETR BOČAN*, ALEŠ JÍRA

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Mechanics, Thákurova 7, 166 29 Prague 6, Czech Republic

* corresponding author: petr.bocan@fsv.cvut.cz

ABSTRACT. This research presents an experimental and numerical analysis of the mechanical properties of very thin polyamide (PA12) samples fabricated by 3D printing with selective laser sintering (SLS). The research methodology focuses on testing mechanical properties such as fracture toughness and simple tensile on PA12 samples ranging in size from 0.50 mm to 2.00 mm, which were then subjected to numerical analysis replicating the experiment. Significant differences between the experimental data and the numerical analysis were found, mainly due to the choice of material model and the selection of inappropriate material parameters. With the numerical analysis, these parameters were appropriately set up and the results of the numerical analysis began to agree more closely with the experimental data.

KEYWORDS: 3D printing, polyamide PA12, fracture toughness experiment, simple tensile experiment, numerical analysis.

1. INTRODUCTION

Currently, 3D printing technology is one of the most advanced methods in additive manufacturing, with widespread use across various industries. This technology makes it possible to create more complex structures, which leads to fostering numerous innovations, making it a highly researched area.

In my previous project [1], I investigated the fracture toughness of very thin polyamide (PA12) samples produced using SLS (Selective Laser Sintering) 3D printing. The experiment was designed following a relevant standard, which determined the geometry of the samples, the experimental procedure, and the final calculation of fracture toughness. The experiment were carried out on samples with widths ranging from 0.50 mm to 2.00 mm. To account for the orthotropy of 3D printed samples, the print orientation was varied, with layers printed either perpendicular or parallel to the anticipated crack propagation. A more detailed description of the experiment and its findings can be found in Section 3.1. Another study [2] also demonstrated the influence of thickness in a simple tensile test, which is more described in Section 3.2.

This project was further supplemented by a numerical analysis conducted using preprocessor GiD and then calculated in ATENA software [3]. The geometry of the numerical model copied that of the experimental samples, and a basic material model was established. The load was defined by deformation in form of displacement. The PA12 datasheet [4] provided only fundamental mechanical properties, such as Young's modulus, tensile strength, and elongation at break. Therefore, additional mechanical properties, such as compressive strength and fracture energy from other experiments, were incorporated into the numerical analysis. Unfortunately, as shown in Figure 1, signif-

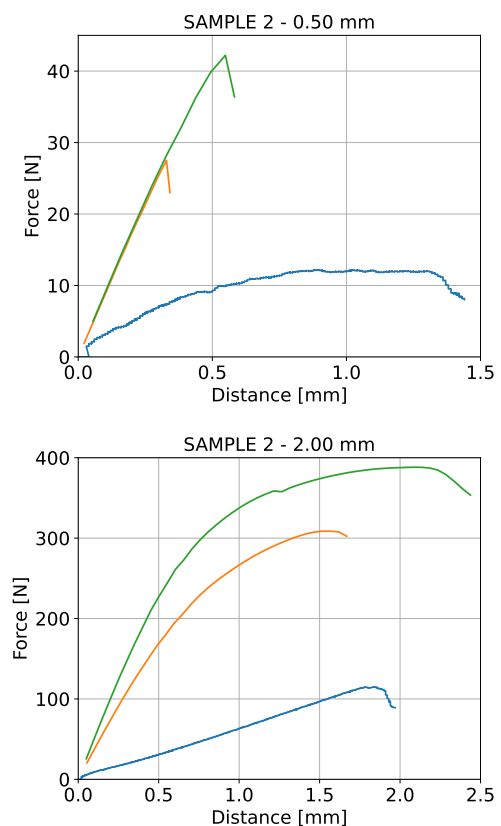


FIGURE 1. Comparison of numerical analysis and experimental data, where the blue curve is the experimental data, orange curve is the linear numerical model and green curve is the quadratic numerical model [1].

icant differences emerged between the experimental and numerical analysis results.

These significant deviations led to a more detailed

investigation into the numerical analysis to identify possible sources of error. The diagrams reveal no match between the linear part of the experimental data and the numerical model, suggesting that the main problem may stem from the chosen material model. In the case of thin samples, the mechanical properties given in the data sheet are insufficient and the values may vary.

As a result, a simple tensile experiment was performed on thin PA12 samples to describe their behavior in the linear region. This experiment enabled the determination of Young's modulus and tensile strength for thin samples, which were then applied to the numerical model under simple tensile loading.

2. MATERIAL AND METHOD OF MANUFACTURE

PA12 (Nylon 12) material was used in my experiment produced by SLS (Selective Laser Sintering) 3D printing technology. Nylons are part of the thermoplastic polymer family and also they are referred to as polyamides (PA) because of their repeating units connected by amide bonds. There are numerous subtypes with varying crystal structures and material properties, including Nylon 6, Nylon 12, and Nylon 66, among others [5]. One of the popular additive manufacturing techniques is Powder Bed Fusion (PBF), also known as SLS. This method is widely used for printing metals and polyamide components by fusing powder particles layer by layer using a high-energy heat source.

Today, 3D printing technologies are extensively used for additive manufacturing in various industries. However, SLS technology presents certain challenges, especially when printing thin samples. One of the main weaknesses is the inadequate bonding of powder particles, and another issue is the inconsistent sample width. Poorly bonded powder particles tend to fall off during handling, which reduces the sample width and weakens its load capacity, ultimately affecting fundamental mechanical properties like the modulus of elasticity. These irregularities can significantly reduce specimen width, influencing the experimental results and subsequently influencing the appropriate choice of material properties in numerical calculation.

3. EXPERIMENTAL PART

Two types of experiments were designed to verify the results of the numerical analysis. First, I started with an experiment dealing with fracture toughness [1], and then I supplemented the research with a simple tensile experiment. Both experiments were conducted on specimens with widths ranging from 0.50 mm to 2.00 mm. The geometries of the specimens were designed according to the relevant standard. A Mark 10 load press was used for loading in both experiments. The fracture toughness experiment was supplemented

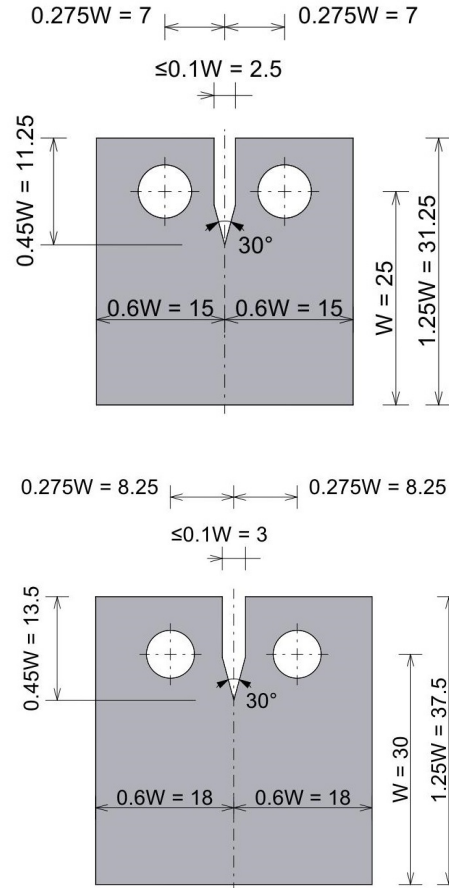


FIGURE 2. The geometries of specimens for fracture toughness experiment according to EN ISO 12737 [6]. Dimensions are given in millimetres.

with 3D macro DIC to monitor crack propagation and crack length readings.

3.1. FRACTURE TOUGHNESS EXPERIMENT

The fracture toughness experiment was carried out according to EN ISO 1273 [6]. With minor modifications, the geometry of the specimens, the experiment procedure, and the final calculation of the fracture toughness value were taken from the standard. In the last research [1], I investigated the fracture toughness of two specimen geometries as shown in the Figure 2.

The calculation of the fracture toughness value K_Q according to the standard EN ISO 1273 [6] is given in the Equation 1.

$$K_Q = \frac{F_Q}{B\sqrt{W}} * f_{(a/W)}, \quad (1)$$

where F_Q is the force determine from the experiment data, B is the sample thickness, W is the length of a ligament.

An essential parameter in the calculation is the geometric factor $f_{(a/W)}$ shown in Equation 2, which is a dimensionless function of a/W , where a is the length of the crack.

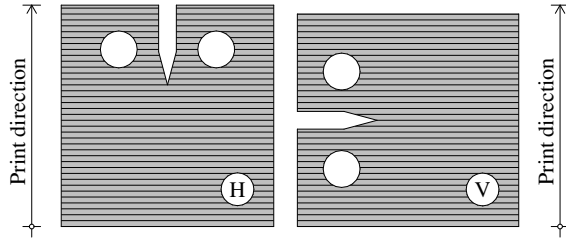


FIGURE 3. Demonstration of the use of orthotropy using different printing direction [1].

$$\begin{aligned}
 f(a/W) = & (2 + a/W) * [0,886 + 4,64(a/W) \\
 & - 13,32(a/W)^2 + 14,72(a/W)^3 \\
 & - 5,6(a/W)^4]/(1 - a/W)^{\frac{2}{3}}. \quad (2)
 \end{aligned}$$

The orthotropy of the material was accounted for by different printing directions (hereafter referred to as H and V). Horizontally (H) printed specimens had individual layers printed perpendicular to the expected crack propagation, while vertically (V) printed specimens had layers parallel to the expected crack. Orthotropy is a material property, where the material has different properties in perpendicular directions. This property is typical for composite materials. Figure 3 shows a schematic of the proposed printing direction.

To refine the adequacy of these results, the fracture toughness values of the PA12 material were determined in other researches. J. Schneider and S. Kumar [7] investigated the influence of ligament length (10, 15, and 20 mm) on fracture behavior. Their study used test samples of 1 mm thick subjected to three-point bending tests. The results demonstrated a clear dependence of fracture toughness K_{IC} on ligament length, with measured values ranging from 3.7–4.5 MPa \sqrt{m} . A. Salazar [8] further examined the effect of three distinct temperature conditions on fracture behavior, reporting fracture toughness values in the range of 2.7–3.2 MPa \sqrt{m} . D. I. Stoia et al. [9] focused on the influence of different printing orientations and processing energy levels. Their experiments resulted in fracture toughness values ranging from 0.8–2.2 MPa \sqrt{m} . In summarizing the results of other experiments, the fracture toughness value for PA12 material was around the values 0.8–4.5 MPa \sqrt{m} [7–9].

Figure 4 showing the average fracture toughness K_Q value for each sample thickness. For the horizontally printed samples with widths of 0.50 mm and 0.75 mm, significant variations in the values were observed, leading to unstable values in results. However, from a certain sample thickness onward, the values became more consistent and began to increase with specimen thickness. The values of the horizontally printed samples ranged from 1.4–2.6 MPa \sqrt{m} . In contrast, for the vertically printed specimens, the fracture toughness values around 1 MPa \sqrt{m} did not increase

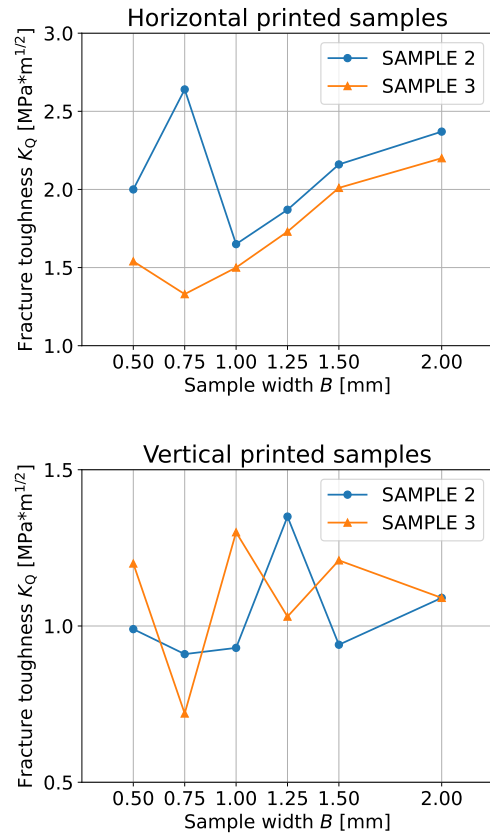


FIGURE 4. Final fracture toughness values for different print thicknesses and orientations [1].

with thickness, remaining relatively constant throughout the tests.

3.2. TENSILE EXPERIMENT

A tensile experiment was conducted by EN ISO 527-1,2 standards [10, 11]. The primary objective of this experiment was to determine the ultimate tensile strength of very thin specimens. Additionally, the experiment aimed to closely examine the linear behavior of thin samples under simple tensile loading. The geometry of the specimens, as specified by the standard, is depicted in Figure 5.

The orthotropy of the material was considered by varying the print orientation, as was done in the fracture toughness experiment. Vertically printed specimens had layers oriented parallel to the tensile load, while horizontally printed specimens had layers perpendicular to the load. The thickness of each printed layer was set to 0.100 mm. Figure 6 provides a schematic representation of the sample printing process for both print orientations.

The small number of samples in the case of 0.50 mm thick samples is due to the heavy handling during the experiment and sample cleaning, and therefore the results for this thickness cannot be considered relevant. The same applies to the 1.25 mm thick samples where only three samples were printed. However, for other thicknesses, an adequate number of samples

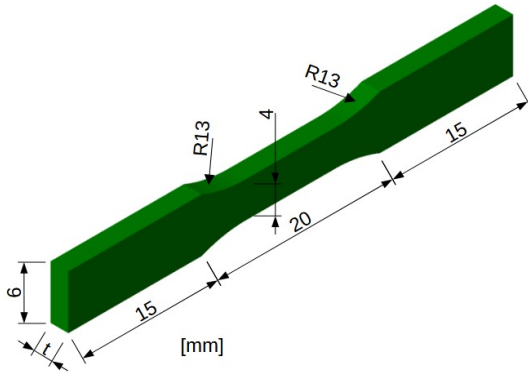


FIGURE 5. Geometry of the specimen used for the simple tensile experiment with variable widths from 0.50 mm to 2.00 mm.

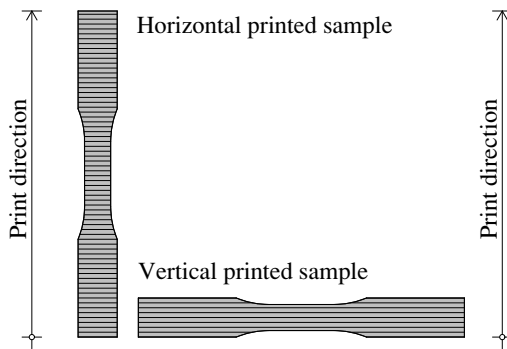


FIGURE 6. Samples print direction for horizontal and vertical samples.

were tested, allowing their results to be considered valid.

In the technical data of PA12 [4], the tensile strength is given as 41 MPa, where it is not specified at which thicknesses or at which print orientation it was found. Therefore, it was necessary to obtain the tensile strength values from other experiments, where the print orientation and thinner samples were my area of interest to search. The studies showed that the orientation of the print and the thickness of the sample are the main factors in the tensile strength values. The Slager study [12] examined different print orientations and thicknesses of the sample, where horizontally printed samples of 0.8 mm ranging around the tensile strength value of 20.5 MPa, for vertically printed samples it was around 27.8 MPa. Sindinger [13] showed a large increase in the value with increasing thickness, where the values for horizontally printed samples were around 25–42 MPa and the values for vertically printed samples were around 26–45 MPa. Other studies have shown that tensile strength is not as much affected by the orientation of the print with increasing thickness [12–15].

The experiment revealed notable differences between vertically and horizontally printed specimens, particularly in the maximum load at which the spec-

Samples widths [mm]	Tensile strength [MPa]
0.50	25.30 ± 0.06
0.75	22.61 ± 1.55
1.00	28.26 ± 1.87
1.25	32.51 ± 1.19
1.50	32.48 ± 0.97
2.00	34.24 ± 2.88

TABLE 1. Tensile strength for the vertically print samples [2].

Samples widths [mm]	Tensile strength [MPa]
0.50	–
0.75	11.76 ± 1.04
1.00	21.29 ± 0.95
1.25	–
1.50	21.16 ± 2.62
2.00	20.07 ± 1.45

TABLE 2. Tensile strength for the horizontally print samples [2].

imens fractured, as shown in Figure 7. From these measurement data was calculated the ultimate tensile strength of each specimen width. The ultimate tensile strength for each specimens were calculated as:

$$f_t = \frac{F_{\max}}{A_0}, \quad (3)$$

where f_t is the tensile strength, F_{\max} is the maximal force from experiment data and A_0 is the cross-section area measured for each samples.

Tables 1 and 2 present the tensile strength results for each specimen width in both print directions. Values are not provided for horizontally printed specimens with widths of 0.50 mm and 1.25 mm due to issues with handling during the experiment and the insufficient number of specimens tested.

As expected, the tensile strength values for vertically printed samples were higher compared to those for horizontally printed samples. This is because vertically printed specimens have layers oriented parallel to the applied load. Conversely, horizontally printed specimens have layers perpendicular to the load, making them more susceptible to breaking with less stress. Anyway, the PA12 technical datasheets [4] specify a tensile strength of 41 MPa, which significantly exceeds the maximum value observed in this experiment. This discrepancy highlights that the manufacturer's certified values may not be applicable for very thin specimens, emphasizing the need for careful consideration of material properties in such cases.

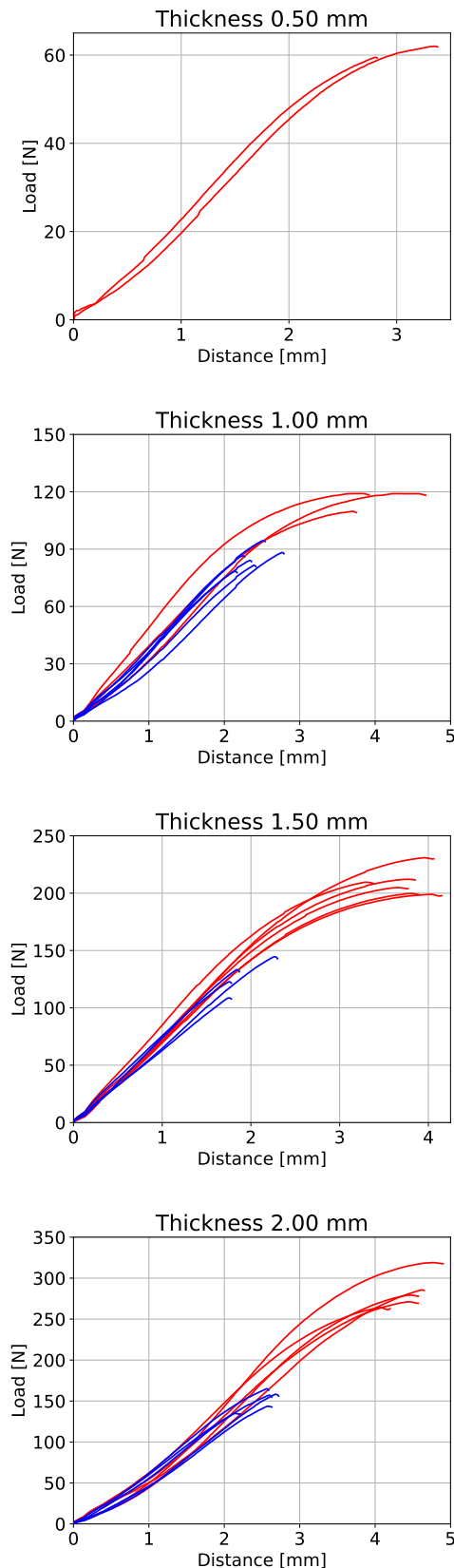


FIGURE 7. Diagrams of Load – Distance values for specimens with widths 0.50, 1.00, 1.50, 2.00 mm. Blue curves indicate samples printed in the horizontal direction, red curves indicate samples printed in the vertical direction [2].

4. NUMERICAL ANALYSIS

The numerical model was developed using GiD 16.0.6 software, which serves as a preprocessor for numerical analysis. Finite element analysis (FEA) was performed with ATENA software [3], typically used for the nonlinear analysis of concrete structures but adaptable for other materials when the appropriate material model is selected. This software excels in numerical simulation experiments, providing detailed insights into crack progression and maximum load capacity before failure.

As mentioned in the introduction, the manufacturer provides limited mechanical parameter information for PA12. The values given in the datasheets include Young's modulus $E = 1.47$ GPa, ultimate tensile strength $f_{t,u} = 41$ MPa and elongation at break $\epsilon_u = 0.13$ [4]. Consequently, the fracture energy G_f and Poisson's ratio μ had to be determined through additional experiments. The material properties used in the FEA for the previous project [1] are given in Table 3.

Material properties	PA12 material
Young's modulus E [GPa]	1.47
Poisson's Ratio μ [-]	0.4
Density ρ [kg m^{-3}]	1010
Thermal expansion α [K^{-1}]	10^{-12}
Tension Strength f_t [MPa]	41
Fracture Energy G_f [kN m^{-1}]	7

TABLE 3. Material properties used in the calculation for previous research [1].

These material properties showed large differences in the FEA results compared to experimental data. It may happen because of the wrong selection of the material model and Young's modulus. Thus, a large parametric study of the simple tensile calculation on the value of effective Young's modulus was performed. The calculation showed the value of effective Young's modulus around 250 MPa, which is 6 times lower than stated by the manufacturer. Also, the material model was set with elasto-plastic behavior using *Cementitious2 - User*.

5. CONCLUSIONS

Previous research [1] investigated the fracture toughness of very thin PA12 samples, involving both experimental and numerical parts. The experimental phase included extensive testing on sample thicknesses ranging from 0.50 mm to 2.00 mm and incorporated orthotropy by varying the printing directions. Numerical analysis was then conducted using ATENA software [3] to simulate the experiments, but significant discrepancies were observed between the numerical predictions and experimental data.

These differences were likely due to an inadequate material model and the selection of inappropriate

material parameters. The material model used had a quasi-brittle behavior, which was not suitable for PA12, as this material exhibits elasto-plastic behavior. It is well established that for thin samples produced via SLS powder technology, manufacturer specified material properties are not directly applicable, and effective material properties for these thin samples must be determined experimentally.

The manufacturer’s datasheet provide limited information on the mechanical properties of PA12, such as Young’s modulus and tensile strength, which can be determined by a simple tensile test. Therefore, this research focused on performing a simple tensile experiment to analyze the linear behavior of the samples under load, which allowed the determination of effective Young’s modulus and ultimate tensile strength for these thin samples. Again, orthotropy with different printing directions was considered.

As with the fracture toughness tests, it was found that the printing direction affects the material’s response to load. Specifically, samples with layers printed parallel to the load direction showed better performance. The experiments demonstrated increasing values with specimen thickness and highlighted substantial differences between the manufacturer’s provided material properties and those obtained through experimentation, as summarized in Table 4. This underscores the fact that standardized parameters cannot be taken into account for very thin samples.

Material properties	Data-sheets	Experiment
Young’s modulus E [GPa]	1.47	0.20–0.26
Tension Strength f_t [MPa]	41	22–35

TABLE 4. The comparison of material properties provided by the manufacturer’s datasheet with the experimental results for vertically printed samples.

The results were verified through Finite Element Analysis (FEA) using ATENA software [3]. Initially, a study was conducted to determine the effective Young’s modulus, which was found to be $E_{eff} = 250$ MPa. This value aligned with Young’s modulus obtained from experimental data. Subsequently, the material model was modified to an elasto-plastic model using the *Cementitious2 – User* option. These adjustments to the material properties and model proved effective, as the numerical analysis results began to closely match the experimental values. Figure 8 shows the result for thicknesses 0.50, 1.00, 1.50 and 2.00 mm, which can be seen there is pretty close agreement between experimental data and FEA results. The small deviations between the experimental data and FEA are due to the choice of one typical value of effective Young’s modulus.

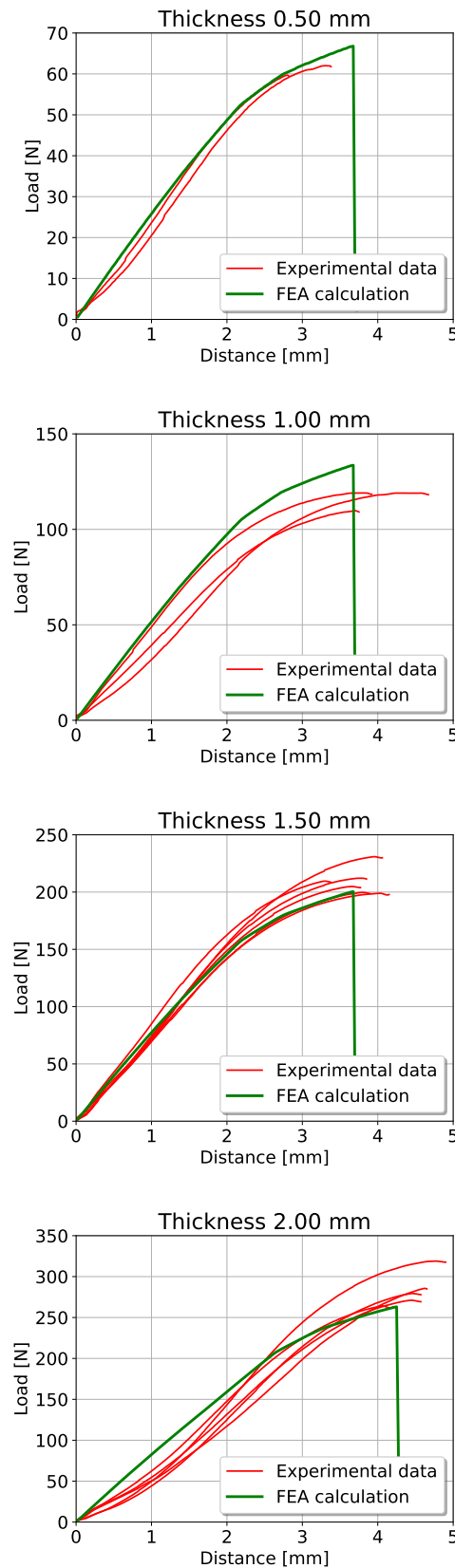


FIGURE 8. Comparison of experimental data of simple tensile and FEA calculation using elasto-plastic material material model and the effective Young’s modulus $E_{eff} = 250$ MPa in the calculation.

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