Study of 3D printing for forming spoke of non-pneumatic tire using finite element method

Chakrit Suvanjumrat\textsuperscript{1,2}, Ravivat Rugsaj\textsuperscript{1,2,*}

\textsuperscript{1}Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Salaya, Nakhon Pathom, 73170, Thailand
\textsuperscript{2}Laboratory of Computer Mechanics for Design (LCMD), Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Salaya, Nakhon Pathom, 73170, Thailand

* Corresponding Author: ravivat.rus@gmail.com

Abstract

Over the last decade, non-pneumatic tire (NPT) was developed by replacing air in traditional pneumatic tire with polyurethane (PU) spoke. However, there are some limitations in building complex shape of spokes. Recently, the 3D printing technique has been used to form complex part of real products. Consequently, it can use to build the complex spoke of NPT. This research aimed to study the possibility of using 3D printing technique to build the complex shape of spoke for NPT. This can be done by studying the mechanical properties of 3D printing material suitable for NPT’s spoke. The PU filament was printed into tensile specimens to carry out the stress-strain relationship by using universal testing machine. The finite element (FE) model of NPT was then created using mechanical parameters of the tension result. The vertical stiffness testing on the NPT model was analyzed. The NPT performance to support the vertical load of real NPT and FE model with original material was carried out to compare with the 3D printing model. Furthermore, the advantage and disadvantage including limitation of using 3D printing technique to manufacture the NPT spoke were discussed.

Keywords: Non-pneumatic tire, 3D printing, Finite element method, Polyurethane

1. Introduction

Non-pneumatic tire (NPT) or airless tire was recently developed as an alternative to traditional pneumatic tire. The NPT utilizes an elastic spoke structure instead of air pressure to support vehicle load and absorb shock from road irregularities [1-3]. The spoke is made of polymer, which is polyurethane (PU) commonly used due to its high elastic properties and durability. Vertical stiffness is a tire property that can be used to indicate NPT’s performance such as load carrying capacity and force-deformation profile [4, 5]. Finite element method (FEM) can be used to predict tire performance upon usage and testing [6-8]. The vertical stiffness testing of NPT can be simulated using FEM. The specimen was prepared from PU spoke of NPT using waterjet cutting technique. The material properties, which were required for finite element analysis (FEA), were derived from stress-strain relationship [9, 10]. The vertical stiffness testing was simulated and compared with the experiments using FEM. The method was
very useful in designing NPT by optimizing the spoke number regarding vertical stiffness [11]. The geometry of spoke structure was found to have significant impact on NPT performance. The FEM can also be used to estimate effect of various spoke geometry to NPT’s vertical stiffness. In addition, the novel NPT was designed and optimized for construction application using FEM [12]. While the FEM was proved to be useful tool for design and analysis of NPT, the proper material modeling corresponding to actual material is required to obtain accurate results.

Recently, 3D printing technique was used to build complex shape spoke for NPT. The acrylonitrile butadiene styrene (ABS) thermoplastic polyurethane (TPU) was used as materials to print honeycomb shear band. The effects of different shear band angles and loading conditions to riding comfort were then studied using the simulation [13]. The 3D printing technique can also be used to study the mechanical characteristic of complex structure. The NPT with anti-tetrachiral spoke structure was designed. The compressive test was carried out on the 3D printed structure, which the gradient type structure was shown good load carrying capacity [14]. As mentioned, the 3D printing technique was shown potential in creating complex part including NPT spoke structure. However, the in-depth study of mechanical properties of 3D printed material is still required. This research aimed to study the possibility to use the 3D printing technique to build the complex spoke structure for NPT. This can be done by studying the mechanical properties of 3D printing material suitable for NPT’s spoke. The 3D printed specimen was prepared and tested to obtain required properties for FEM. Thus, the FEM of vertical stiffness testing of NPT was analyzed and compared with the actual NPT.

2. Specimens Preparation

2.1 3D printed specimens
The dumbbell shape specimen is prepared using the 3D printing technique according to ASTM D638 (Figure 1). The 3D printing machine, Sync Innovation C300, is developed by Sync Innovation corp., is used with printing parameters as shown in Table 1. As thermoplastic polyurethane (TPU) is suitable material for NPT spoke structure due to its high strength and flexibility. The Armadillo 3D printing filament for fuse deposition method (FDM), which was developed by Ninjatek corp., was used as printing material. The mechanical properties and some important printing properties as stated in its specification are shown in Table 1. The rectilinear printing pattern with 45% infill angle was selected as part of printing parameters.

2.2 Waterjet cut specimens
The NPT TWEEL 12N16.5 ALL TERRAIN, is developed by Michelin, is selected as subjected NPT in this research (Figure 2(a)). The spokes are extracted from the NPT using waterjet cutting technique (figure 2(b)). After that, the spoke is cut into dumbbell shape specimens using a die cutting machine according to ASTM D412 (Figure 2(c)). The spokes were sliced until a required thickness of 2 mm was obtained. In addition, the spokes were cutting with 2 directions, which is radial and width direction relating to the NPT, to study the effects of material’s direction dependence.
Table 1. 3D printing parameters and Mechanical properties of Armadillo 3D printing filament.

| Parameters            | Value | Properties          | Value |
|-----------------------|-------|---------------------|-------|
| Nozzle temperature (°C) | 235   | Density             | 1.18  |
| Bed temperature (°C)  | 50    | Melting temperature (°C) | 212   |
| Printing speed (mm/sec)| 20    | Yield stress (MPa)  | 27    |
| Layer thickness (mm)  | 0.2   | Ultimate stress (MPa) | 48    |
| Infill pattern        | Rectilinear | Modulus of elasticity (MPa) | 396 |
| Infill angle          | 45°   | Elongation at yield (%) | 18   |
| % infill              | 100%  | Elongation at break (%) | 295  |

Figure 2. (a) The NPT, TWEEL 12N16.5 ALL TERRAIN, (b) the extraction of spokes using waterjet cutting technique, and (c) a waterjet cut specimen.

3. Mechanical Properties Testing

The 3D printed specimens and waterjet cut specimens are tested using universal testing machine (UTM), Instron 5969, as shown in Figure 3(a). The tensile tests are performed on both 3D printed (Figure 3(b)) and waterjet cut specimens (Figure 3(c)) according to ASTM D638 and ASTM D412, respectively. The tests were performed on 5 specimens for both preparation methods to ensure reliability and repeatability of the results. The stress-strain relationships obtained by the tension test on specimens can be plotted as shown in figure 4. The mechanical properties required for FE modelling can be summarized as shown in Table 2. It was found that waterjet specimens show nearly identical stress-strain profile for radial and width cutting direction. However, the ultimate stress and breaking stress were found to be significantly different.

Figure 3. (a) The UTM, Instron 5969, (b) tensile testing of 3D printed specimen, and (c) tensile testing of waterjet cut specimen.
4. Finite Element Analysis of NPT

The FE model of NPT was created and the conditions were applied using FE software, MSC. Patran. The FE mesh of NPT along with its dimension are shown in Figure 5(a). The tread and shear band were modeled using continuum element, while the spoke was modeled using shell element. The linear elastic or Hookean material model was used to model the mechanical behaviour of NPT’s components. The details of elements used in modelling the NPT are summarized as shown in Table 3. Each component is assembled together using glued contact condition just like the actual NPT assemble process as shown in Figure 5(b). The belt layers were modeled using reinforce bar or rebar element. They were embed into shear band element using tying equation. The comparison of embed rebar element and actual belt’s position is shown as schematic diagram in Figure 5(c). In addition, each rebar element composed of mathematically sublayers of belt. The outer layers, middle layers, and inner layers composed of 3, 1, and 2 sublayers, respectively. The bead wire diameter was estimated by measuring to be 1 mm, while the number of wires per unit length was estimated to 0.3582 mm$^{-1}$.

The simulation of vertical stiffness testing was performed using FE software, MSC. Marc. The FE mesh of NPT is combined with rigid plate, which represented tire testing machine’s moving plate as shown in Figure 6(a). The contact algorithm with Coulomb’s friction of 0.8 was used to calculate interactive force between NPT and rigid plate. The plate was assigned to press upward against the NPT in vertical direction with force of 20 kN or until the displacement of 26 mm was obtained. The NPT was assigned to be fixed at the inner spoke portion. This represented the locking adapter at the rim in the actual experiment. The analysis was then performed and the results were collected.

| Specimens          | Minimum breaking strain | Average breaking strain | Ultimate stress (MPa) | Modulus of elasticity (MPa) |
|--------------------|-------------------------|-------------------------|-----------------------|----------------------------|
| 3D printed         | 10.40                   | 10.87                   | 25.53                 | 26.52                      |
| Waterjet cut, radial dir. | 11.52                   | 12.98                   | 32.92                 | 42.47                      |
| Waterjet cut, width dir. | 6.06                    | 9.26                    | 17.24                 | 38.29                      |
Figure 5. (a) FEM of NPT, (b) components of NPT, and (c) comparison of embed rebar element and actual belts’ position.

Table 3. Details of FEM of NPT.

| Parameters                          | Tread         | Shear band    | Spoke         | Belts         |
|-------------------------------------|---------------|---------------|---------------|---------------|
| Element type                        | Hexagonal     | Hexagonal     | Quadrilateral | Quadrilateral |
| Number of node per element          | 8-node        | 8-node        | 4-node        | 4-node        |
| Number of element                   | 2,288         | 11,904        | 35,500        | 6,144         |
| Average element edge length (mm)    | 19.36         | 16.15         | 8.74          | 20.38         |
| Average element thickness (mm)      | -             | -             | 5.8           | -             |
| Modulus of Elasticity (GPa)         | 8             | 32            | 26.52/42.47   | 200           |

Figure 6. (a) Tire testing machine, Ektron PL-2003, (b) FE model of vertical stiffness testing of NPT, and (c) boundary conditions.

5. Results and Discussion

FEA of vertical stiffness testing of NPT was performed and the results were achieved. The stress and deformation results of FEA of both 3D printed and waterjet material are shown on Figure 7. The maximum stress value at spoke and deformation was found to be high on the 3D printed model due to
its lower modulus of elasticity. The maximum stress value at spoke of both models are summarized in table 4. The maximum of stress that occurred on 3D printed NPT was estimated to be 12.21% higher than the waterjet cut one. As the yield stress value was roughly estimated to be 6 MPa from the mechanical properties testing, the safety factor of 3D printed model and waterjet cut model was then estimated to be 4.08 and 4.58 times, respectively. It should be note that the tension was observed on the upper portion of spoke on both models. On the other hand, the bending and compression were observed on the lower portion of spoke on both models. This indicate the feature to uniformly distribute the load along all portion of spoke, not only on the lower portion which was directly contact the plate.

The vertical force and displacement were then collected. In addition, the force and displacement data were also collected from the vertical stiffness testing experiment of actual NPT. The experiment is performed by tire testing machine, Ektron PL-2003 (Figure 6). The vertical force and displacement relationship of the experiment and both FE model are plotted as shown in Figure 8. The vertical stiffness could be derived from ratio between vertical force and displacement. The estimated vertical stiffness values of FE models and experiment are shown in Table 5. The FEM’s analysis error could be estimated by comparing between the waterjet FE model and the experiment because they were based on the same material and conditions. The comparison showed that the estimated vertical stiffness has error of 9.14%. There were proved the validity and accuracy of the FE model. According to the validated model, the vertical stiffness of NPT with 3D printed material is estimated to be 82.68% of original NPT made by traditional molding method. This indicate the mechanical performance and load carrying capacity of 3D printed NPT should be around 82.68% of original NPT as well. While the performances, which including maximum stress and vertical stiffness, of 3D printed NPT was found to be lower than original NPT, the 3D printing technique was proved to be superior in creating complex spoke shape for NPT. The difference in performance was found to be minor difference and negligible.

![Figure 7](image)

**Figure 7.** Maximum stress at spoke and deformation of: (a) 3D printed NPT and (b) waterjet cut NPT.

|                          | Experiment | FEM, 3D printed | FEM, waterjet cut |
|--------------------------|------------|-----------------|-------------------|
| Vertical stiffness (N/mm)| 869.93     | 653.49          | 790.42            |
| Maximum stress (MPa)     | -          | 1.47            | 1.31              |
| Safety factor            | -          | 4.08            | 4.58              |

|                          | Stress (MPa)                                 |
|--------------------------|----------------------------------------------|
|                          | 1.31                                         |
|                          | 1.18                                         |
|                          | 1.04                                         |
|                          | 0.91                                         |
|                          | 0.89                                         |
|                          | 0.88                                         |
|                          | 0.84                                         |
|                          | 0.80                                         |
|                          | 0.76                                         |
|                          | 0.72                                         |
|                          | 0.68                                         |
|                          | 0.65                                         |
|                          | 0.62                                         |
|                          | 0.59                                         |
|                          | 0.56                                         |
|                          | 0.52                                         |
|                          | 0.49                                         |
|                          | 0.46                                         |
|                          | 0.43                                         |
|                          | 0.39                                         |
|                          | 0.36                                         |
|                          | 0.33                                         |
|                          | 0.29                                         |
|                          | 0.26                                         |
|                          | 0.22                                         |
|                          | 0.19                                         |
|                          | 0.16                                         |
|                          | 0.13                                         |
|                          | 0.09                                         |
|                          | 0.06                                         |
|                          | 0.03                                         |
|                          | 0.01                                         |
|                          | 0.00                                         |

**Table 4.** Vertical stiffness and maximum stress of experiment and FEA results.
Figure 8. Vertical force and displacement of FEA compared to the experiment.

6. Results and Discussion
This research aimed to study the possibility to use 3D printing technique to build complex spoke structure for NPT. The conclusion can be summarized as follows:

1) The tensile specimens were prepared from 3D printing technique and waterjet cut from original NPT. The stress-strain relationships were collected by using UTM. The modulus of elasticity of the 3D printed specimen and waterjet cut specimen were found to be 26.52 and 42.47 MPa, respectively. The average breaking strains were found to be nearly identical at 10.87 and 12.98, respectively.

2) The FE model of NPT was then created using mechanical parameters of the tension result. The vertical stiffness testing on the NPT model was analyzed. The maximum stress of 3D printed NPT and waterjet cut NPT were found to be 1.47 and 1.31 MPa, respectively. This indicated that the maximum of stress that occurred on 3D printed NPT was estimated to be 12.21% higher than the original NPT.

3) The vertical force and displacement were then collected from FEA and the experiment. The vertical stiffness was then calculated from vertical force and displacement relationship. The vertical stiffness of the experiment, FEM of 3D printed NPT, and FEM of waterjet cut NPT were found to be 869.93, 653.49, and 790.42 N/mm, respectively. The simulation error was found to be 9.14% compared to the experiment. The vertical stiffness of NPT with 3D printed material was estimated to be 82.68% of original NPT.

The results of this research indicate that the 3D printed NPT’s performances, which including maximum stress and vertical stiffness, was found to be lower than original NPT. The performances of 3D printed NPT were found to be not significantly different to model NPT. However, the 3D printing technique was proved to be superior in creating complex spoke shape for NPT. Thus, the technique should be useful in development of NPT in the near future.

Acknowledgments
This work was financial supported by Rubber Technology Research Center and the Thailand Research Fund (TRF) under the TRF Research Grant No. RDG60T0140, and RDG62T0026.

References
[1] Gasmi A Joseph P F Rhyne T B and Cron S M 2012 International Journal of Solids and Structures 49(13) 1723-1740
[2] Ju J Kim D-M and Kim K 2012 Composite Structures 94(8) 2285-2295
[3] Phromjan J and Suvanjumrat C 2018 *Journal of Mechanical Science and Technology* **32**(4) 1539-1548

[4] Rugsaj R and Suvanjumrat C 2020 *IOP Conference Series: Materials Science and Engineering* **773** 1-4

[5] Jin X, Hou C Fan X Sun Y Lu J and Lu C 2018 *Composite Structures* **187** 27-35

[6] Phromjan J and Suvanjumrat C 2018 *Engineering Journal* **22** 141-155

[7] Phromjan J and Suvanjumrat C 2018 *Key Engineering Materials* **777** 416-420

[8] Phromjan J and Suvanjumrat C 2018 *Key Engineering Materials* **775** 560-564

[9] Rugsaj R and Suvanjumrat C 2018 *Key Engineering Materials* **775** 554-559

[10] Rugsaj R and Suvanjumrat C 2018 *Key Engineering Materials* **777** 411-415

[11] Rugsaj R and Suvanjumrat C 2019 *International Journal of Automotive Technology* **20**(4) 801-812

[12] Rugsaj R and Suvanjumrat C 2020 *Mechanics Based Design of Structures and Machines* In press

[13] Kannan P Shaik A Kumar Y and BReddy N S 2019 *SAE Technical Paper* 2019-28-0059 (United State: SAE International)

[14] Wu T Li M Zhu X and Lu X 2020 *Mechanics of Advanced Materials and Structures* In press