Numerical-experimental approach to assess the deflection behaviour of carbon fibre fishing rod

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Abstract. Deflection of a commercial hollow type fishing rod is investigated in this research. The fishing rod of interest is of Abu Garcia brand, made of carbon fibre. Analytical, experimental and numerical approach were performed to assess the bending of the rod under maximum 1.25 kg load located at the tip which represents the rod in pulling. The deflection is defined by longitudinal displacement of each point of guide rings located along the fishing rod. A mathematical model based on basic bending theory of cantilevered beam is formulated to obtain the deflection and then experiment was carried out by immobilizing one end horizontally on the wall and applying at tip force. The final position of the rings was marked, and the displacements were recorded. Finite element model was developed as an isotropic and elastic material via ANSYS software. Results from all approach were compared and it was found that analytical and numerical able to predict a similar trend of bending behaviour. However, large discrepancies were observed in the experimental curves due to several reasons.

1. Introduction
In this urban era, catching a fish is no longer an activity to earn a living, it also considered as a hobby and sport for some enthusiast. But similar to traditional way of fishing, an angler needs a fishing rod, line, and lure to fish whether in recreational or sport fishing. Although the literatures of fishing are abundance and dated back from the 80’s, but there were mostly reported on the experiential studies while the scientific studies of fishing are still limited [1]. The improvements in fly fishing equipment have been rapid over the last 10-20 years. This improvement is due to increased knowledge about the physics of fly casting, development of more efficient casting techniques and technical development of the equipment.

The development of fishing rod manufacturing has led to light and stiff rods. These modern rods allow the caster to insert a high line speed, thus enabling a large amount of movement energy into the fly line[2]. The construction material of a rod affects the flexibility of the rod when a pressure is put at the tip of the rod. Rod can be created from different materials with different layers, all of which contributes to the responsiveness of the rod. Throughout the history, wood, bamboo, steel and fibreglass have been used as the fishing rod. Common material of modern fishing rods is high performance carbon fibers which can be classed in three categories, high resistance (HR), intermediate modulus (IM) and high modulus (HM) having modulus greater than 400 GPa [3].

Fishing rod design stage is a complex process that needs timely trial-and-error approach. In preliminary design work of a conventional rod fabrication, deflection board is used to gain sight of a
finished rod that bends under load. One major disadvantage of this test is the rod must be finished before its flexural properties could be determined. Plus, it involves high pre-prototyping cost and enormous time effort. Such complications have led to the development of analytical analysis and numerical procedure to reduce unnecessary physical testing.

Theoretically, the bending or deflection of fishing rod is regarded as a tapered cantilever beam as employed by most studies [1], [4]–[6]. One of the earlier recognized works on modelling it mathematically is Leonard Euler in 1744 and succeeded later on by Jacob Bernoulli, Johann Bernoulli and L. Euler [4], [7]. Euler described the bending as large deflection of flexible rod where under loading, the free end will be subjected to a certain degree of deflection path. Ghuku and Saha had done a comprehensive literature of large deflections behavior of curved beams and reported that when an initially straight beam is subjected to pure bending moment, Euler-Bernoulli beam theory states that the bending moment is proportional to the change in curvature and was originally developed in geometrical nonlinear kinematic setting [7]. Thus, it is assumed that bending does not alter the length of the beam.

In the earliest reported research had done by Ohnishi and Matsuzaki. They analysed graphite type fishing rod to predict fracture location [8]. Both experimental and finite element approach were applied and they found a good agreement between those results. In a different study, Guan had numerically evaluated the bending of tubes with various cross-sectional shapes [9]. Finite element, FE models were developed to simulate the deformation of fishing rod by employing elastic constitutive model as well as nominal material properties. Guan introduced specific cross-sectional shape which is best for anglers called "Reuleaux Triangle".

One of important work specifically for a hollow, circular and tapered fishing rod was done by Otsuki in Ohtsuki [10] and [4]. Otsuki performed the experiment by fixing and tilting the rod by a certain degree and applying load at free tip. Later the experiment was compared to theoretical result based on large-deformation theory and both approach obtained good agreement. From the finding, the large-deformation theory is proven as best mathematical model to represent the deflection of fishing rod. However, complex calculation is required and in the above case, even the Runge-kutta-Gill method is adopted to carry out the solving of equation involved numerically. While Chang were focusing on the nonlinear mathematical and FE modelling of fishing rod under static and dynamic response.

Thus the objective of this study is to simulate the bending of a commercial fishing rod under loading by means of simple analytical and numerical approach via ANSYS software, and compare the performance with experimental setup. While previous researches utilized the complex-to-derived large-deformation theory, here the basic bending theory of tapered and cantilevered beam was applied. Comparison between all approaches will demonstrate the applicability of the bending theory for a simpler method, and the reliability of numerical analysis using a commercial FEA software.

2. Methodology
Investigation were done by replicating bending behavior of Abu Garcia™ fishing rod which is made of carbon fiber. The Young's modulus in 0° fiber direction is taken 175 GPa with Poisson's ratio of 0.3 based on the material's general properties [11]. As in Figure 1, the structure of the rod is a cylindrical hollow type and the diameter is decreasing from the butt towards the tip. The length of bending part is 1.525 m. Six points were marked from the end of bending part of the rod (at handle grip) to the tip which represents the string placers or guides. The position of guides were labelled as \( \partial n \) (where \( n = 1, 2, 3,..., 6 \)) their values are shown in Table 1. Load applied were ranged from 0.25 kg to 1.25 kg with the increment of 0.25 kg per step. Figure 2 shows the experimental setup of the fishing rod while loading and Table 1 lists the deflection points distance from the handle.
Figure 1. The detailed drawing of Abu Garcia fishing rod of total length 2153 mm. The length of the bending rod was taken as 1525 mm and six markers were placed along this length to represent guides as summarized in Table 1.

Table 1. Deflection points location from grip

| Indicator | Deflection | Location (m) |
|-----------|------------|--------------|
| Point 1   | $\vartheta_1$ | 0.435        |
| Point 2   | $\vartheta_2$ | 0.755        |
| Point 3   | $\vartheta_3$ | 1.000        |
| Point 4   | $\vartheta_4$ | 1.215        |
| Point 5   | $\vartheta_5$ | 1.395        |
| Point 6   | $\vartheta_6$ | 1.525        |

Figure 2. The experimental setup of fishing rod under loading. The reference line represents the origin line, $\delta$ is the longitudinal deflection of rod measured from reference, and $x$ is lateral displacement measured from reference.
2.1. Mathematical Model of Fishing Rod

Fundamental bending moment, M of a beam is applied where the fishing rod is assumed as a rigid cantilever beam with one fixed end. Consider a long, thin cantilever leaf spring (Figure 3) where \( L \) is the length of the rod, \( x \) is the horizontal component of the displacement of the loaded end of the rod, \( \partial \) is the corresponding vertical displacement, \( P \) is the concentrated vertical load at the free end, \( B \) the flexural stiffness of the rod’s material mathematically expressed as \( B = EI \) where \( E \) is the modulus of elasticity and \( I \) is the moment of inertia.

![Figure 3](image.png)

**Figure 3.** Free body diagram of fishing rod subjected to vertical load, \( P \)

The equation and derivation with elastic curve [12] is as in Equation 1 below:

\[
M = -Fx
\]  

(1)

By two order of integration and applying boundary conditions, Equation 1 becomes:

\[
\partial = -\frac{P L^3}{3B}
\]  

(2)

With this, Equation 2 serves as the theoretical model in predicting the deflection of all six points on the fishing rod.

2.2. Bending experiment of fishing rod

The experiment setup was employed from Ohtsuki [10], the fishing rod is treated as a cantilevered beam fixed at one end. A new Abu Garcia fishing rod was fixed on a wall, at the handle to represent the fixed end from the theory and resembles the angler’s holding the rod (see Figure 4). Grid of 10 x 10 cm² made of A0 paper was pasted on the wall. The handle of the rod was fastened and immobilized so that only the free end of the rod could deflect under stress. The stress was transmitted to the rod by means of a thin nylon fishing line attached at the tip of the rod and pulled horizontally at a force measured by an attached digital scale calibrated accurately to 0.01 lb (0.0445 N). For every load from 0.25 kg to 1.25 kg (increment of 0.25 kg), the final position of each guide was recorded and marked on the paper.
Figure 4. Experimental setup for bending of fishing rod consist of immobilized fishing rod, and A0 paper pasted on the wall to record the deflection of the rod free end.

2.3. Numerical Assessment of Fishing Rod

The deflection of fishing rod is simulated by ANSYS software as a linear, elastic and isotropic material. Material properties and actual dimensions including rod's handles as in Table 1 and Figure 1 respectively were utilized to generate the FE model. The analysis type is static (steady-state) with 1 x 1 meshing element size at all segments. The 3-noded element was used and the boundary condition is fixed end at left hand side as shown in Figure 5. The simulation was only considering the longitudinal deflection of the rod.

Figure 5. Simulation of the elastic curve calculated numerically using ANSYS software using $E= 175$ GPA for $F=0.25$ kg. The boundary condition is fixed end at left hand side.
3. Result and Discussion

A comparison of theoretical and experimental deflection curves for weight 0.25 kg (2.4524 N) through 1.25 kg (12.263 N) is shown graphically in Figure 6 respectively. Generally, it is found that the bending deflection distributions of the fishing rod vary with the point location which shows the minimum bending strain travels from the tip to butt area with increasing load.

From the figures, it was shown that comparable profile for theoretical and numerical is achieved for load of 2.4524 to 12.263 N which presumably indicates that the rod satisfied the assumptions of basic large cantilevered beam under deflection. It was observed that at any specific location, the deflection differences for each loading are in a close range, except beyond point 4. This might suggest that the finite element model does not have sufficient parameters to predict the deflection of such fishing rod. The current element model should be further refined for a proper meshing procedure, considering the tube type structure of the fishing rod. In addition, a gradient property is existing which is in this study, is the variation of flexural strength due to the decreasing of structural cross-sectional area towards the tips.

![Deflection Curves](image)

*Figure 6. The deflection curves for theoretical, numerical (FEA) and experimental of bending fishing rod subjected to load 2.45, 4.905, 7.3575, 9.81 and 12.26 N respectively.*

The comparable profiles of rods show an excellent fit of theory to numerical for approximately the initial 60% of the rod length and then a slight deviation for all five loads. The divergence seems like a
phase change with discontinuous slope and presumably occurred neither from random or systematic error in the collection or processing of the data. The deviation pattern signifies a failure of the rod to fit to one or more of the assumed conditions for the validity of the theory for Equation (2) as in agreement with Silverman et al [6].

The experimental graphs for all load levels show extreme deviations from both theoretical and numerical could imply that there was a significant systematic error involve in data processing such that the fishing rod was modelled as having a uniform cross-section throughout its length, but the rod used has a geometry variation at the tip end. The length of the rod is also assumed to be unchanged for each loading condition for the theoretical analysis, which is contradict with the experimental finding, as suggested by Ghuku and Saha. According to their research, it was suggested that the experimental load condition has an eccentricity that will change the effective length of the rod at each loading [13]. Besides, it is possible that the geometry variation along the rod could also come with variation of stiffness. Silverman et al suggested that the flexural rigidity or known as stiffness among the rod manufacturers may varies along the rod length [6] since stiffness is the product of a material parameter ($E$) and a geometric parameter ($I$), thus either or both can effect a change in flexural rigidity.

Plus, the variance occurred probably due to the inaccurate value of Young’s modulus used in theoretical and numerical setting, as we have been unable to find any values of $E$ reported by rod manufacturers or vendors for their rod. The Young’s modulus value should be calculated using ANSYS by comparing the longitudinal deflections obtained from experiment with the numerically obtained values. It is possible that the value of modulus should be higher than 175 GPa.

In addition, it was observed that there exists slight deflection in experimental curves at point 1, whereas the deflection is missing in both models. This may due to the present of uniformly distributed load along the length of rod which is not considered in theoretical (Equation 2) and numerical analysis. Besides, the large deviation could be explained by the fact that the actual rod is using nylon string to hold the weight while the models eliminate this consideration in calculation. The actual bending of rod under loading is affected by the string not only at the tip, but other guide was pulled at the same time. Those guides (excluding the one at the tip), might had been introduced to extra load by the action of the string. Thus, larger deflections were observed experimentally.

4. Conclusion
Mathematical model and finite element model have been successfully developed to simulate the deflection of Abu Garcia fishing rod and compared to those obtained from the experimental setup. It is found that both approaches can predict a similar trend of bending behaviour. Large discrepancies were observed between experiment and theoretical prediction suggesting that the basic bending theory is less practical. Close range of errors are exhibited at their respective points which indicates that the FE model is lack of few parameters. Both methods could further produce more accurate deflection given that a material property of the fishing rod are reliably established by conducting physical experiments such as flexural test or numerically calculated. In addition, it is more reliable to take into consideration that the rod has a non-uniform geometry along its length, thus a better and accurate mathematical and numerical model can be approached. Plus, addition of horizontal displacement in x-axis is necessary for the best prediction of the deflection path.

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