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Concerns about Deteriorated Nano-Fiber Reinforced Composite as Candidate for Renewable Energy Applications

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Abstract

Nanocomposite has become nowadays best candidate to be used for renewable energy applications due to its superior properties which open the doors for more prospects in term of the engineering challenges as well as economic opportunities. On the other hand, it cannot be avoided that the existence of internal defects through the manufacturing process of the materials. This lead to over consumption of the raw material in overcoming this weakness, especially stiffness of the composite materials that are intensively used to manufacture renewable energy structures and elements to reduce weight impact and hence minimize emissions. In this analysis, a deteriorated nanofiber reinforced composite is studied using finite element method to predict how the nano-debonding affects the stiffness of the composite. It is clearly evident that the major lost in the nano-composite stiffness was between 7.5-10% for the fully deterioration, whereas the minimum reduction was between 2-2.5% for the minimum defective RVE.

Keywords : FEM, interfacial, nano-composite, renewable energy, stiffness.
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1. Introduction

Renewable energy development is considered as one of the most technological challenges since it is connected with a collection of aspects that are related to the consumption and production of energy. The rapid progress in the nanotechnology made it as a candidate to resolve many of renewable energy concerns. The reduction in the size of many things due to this technology led to a reduction in the energy consumption through different ways, which can gain many advantages as a result. The main advantages that can be achieved from the design of nanotechnology based products for renewable energy which are an increased efficiency of lighting and heating, increased electrical storage capacity, a decrease in the amount of pollution from the energy using and nanotechnology will generate big investment [1]. An improvement can be achieved through nanotechnology to the renewable energy especially for wind turbine efficiency by using light material, high strength composite materials for rotor blades or even for turbine gear box [2], whereas traditional materials like steel and concrete are still dominate the global renewable energy

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structures [3] . So using nano-composite is very effective in developing renewable energy applications, but unfortunately in the other hand nano-composite may contain internal nano-flaws this would reduce the stiffness of the composite and hence forces engineers to add more thickness to overcome this problem. Many researches have focus on improving mechanical and the thermal properties of the nano-composite [4], whereas the impact of the nanotubes on the nano-composites was investigated as well [5]. As a matter of fact, it has been know that there are three mechanisms of interfacial load transfer between nano-fiber and the polymeric matrix, which are the weak van der Waals force, chemical bonding and micromechanical interlocking [6]. It is well known that there are two causes behind a mechanically strong or weak nano-composite material which affects the stiffness and the matrix interface with the nano-fibers and the stress transfer. Stress concentrations will take place at the matrix/nanofiber interface, as the nano-composite subjected to a mechanical loading, which will eventually lead to deterioration of the nano-composite and finally leads to damage nucleation, initiation, growth and final non-tolerated failure [7]. Basically, there are two apparent sources of damage nucleation in nano-composites; poor wetting of the nano-fibers by the polymer and the aggregation of the nanofibers [8]. Both cases produce polymer rich nano-composite portions that are likely to experience low stress to failure. Low strain to failure to the high interfacial stress is one of the reasons that nano-composites may have caused nano-fiber/matrix nano-debonding as observed by researchers [9] . Mainly, the factor that will indicate the final nano-composite material strength is the stress transfer from the matrix to the reinforcement. Moreover, local interfacial properties affect the macro level of the material behavior, like decreasing in the flexural strength in nanotube/epoxy composite beams due to weakly bonded interfaces [10], as well the reduction in composite stiffness attributed to local nanofibers/ nanotube waviness [11]. Deterioration of the nano-composite mechanical properties can be ascribed to many factors; therefore it has been attracted by many scholars to investigate the mechanical properties in addition to the parameters that play main role in the predicted properties. The effect of the interfacial matrix/nano-fiber crack [12, 13], mismatch properties [14] and the embedded nano-inclusions [15, 16] on the interfacial stresses in nano-composite were investigated via finite element analysis, whereas nano-debonding defects were investigated to predict the mechanical characteristics [17]. A comparative study on the nano-composite defects was demonstrated by Ahmed [18]. Gawandi et al. [19] studied the impact of the nano-fiber elastic properties and toughening effect of the nanofiber by 3D finite element analysis of a penny-shaped cracked matrix as well as the influence of a mismatch, whereas a representative volume element of a simplified 3D model for a wavy carbon nanotube is adopted [20] to investigate the stress transfer in single wall carbon nanotube composites. A computational numerical-analytical model of nano-reinforced polymer composites was developed taking into account the interface and particle clustering effects [21]. Mainly Yijun et al. [22] used advanced boundary element method to study curved cracks at the inter-phases between the fiber and matrix in the fiber reinforced composites, where stress intensity factors were evaluated. Three different approaches were discussed in finite element modeling, i.e. multiscale representative volume element modeling, unit cell modeling, and object-oriented modeling [23]. Also, the mechanism of nano-composite mechanical property enhancement and the ways to improve stiffness and fracture toughness for nano-composites were discussed. Unnati et al. [24] studied the effects of pinhole defects on the mechanical properties for wavy carbon nanotubes based nano-composites using 3-D representative volume element with long carbon nanotubes. The effective mechanical properties of carbon nanotube-based composites were investigated using a square RVE based on the continuum mechanics and with FEM [25]. A developed FEM based on molecular mechanics to predict the ultimate strength and strain of single wall carbon nanotube, and the interactions between atoms was modeled by combining the use of non-linear elastic and torsional elastic spring [26]. Hernández-Pérez and Avilés [27] studied the influence of the interphase on the effective properties carbon nanotube composites using FEA and elasticity solutions for RVEs. A proposed single wall carbon nanotube-FEM, based on the use of nonlinear and torsional spring elements is adopted [28] to evaluate the mechanical properties.

In the present analysis, interfacial nano-debonding in nanofiber/matrix was investigated using finite element method (FEM) to predict the impact of the nano-debonding on the stress intensity factor through using linear elastic fracture mechanics, where the nano-debonding was modeled as a crack. Mechanical properties of the nano-composite were predicted through estimating effective stiffness (i.e., Young's modulus) of the nano-composite. Moreover, further study was done to explore the interfacial stress distribution along the transverse as well as the longitudinal sides of the nanofiber for both intact and the defective (i.e., debonded nan-ofiber) nano-composite. A representative volume element was selected to represent the nano-composite and subjected to uniaxial tensile stress, as shown in Figure 1.

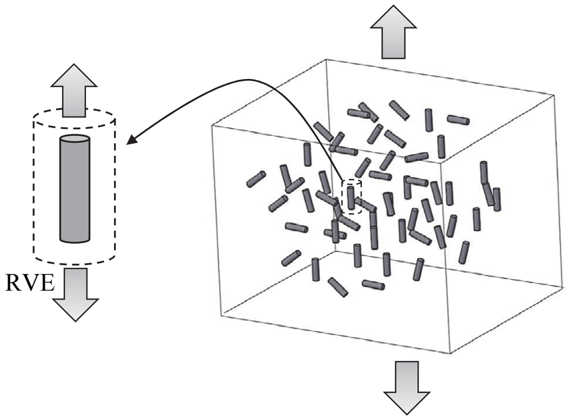

Fig. 1: RVE under uniaxial load.

2. Finite Element Analysis

In general, molecular dynamics simulations are usually used to deal with physical phenomena at the level of a few nanometers [29], whereas finite element analysis has been implemented in the present study to be the main tool instead. The range 20-50 nm is considered as the smallest dimension of the nano-fiber investigated, which means continuum mechanics fundamentals used in the finite element analysis is still valid and applicable at such scales. Mainly, homogeneous, elastic, isotropic, residual stresses free are the assumptions adopted in the analysis of the nano-composite. In general, the material used for the RVE is modeled through a matrix having a modulus of elasticity of 4 GPa and Poisson's ratio of 0.4, whereas the nano-fiber is proposed to have Young's modulus of Ef = 200, 400 and 800 GPa, where the stiffness ratios are E_f/E_m=50, 100 and 200 [11]. A uniaxial pressure of unit nN/nm^2 is applied along the RVE in tensile mode. The RVE length and the diameter considered in the analysis are 120 nm and 90 nm respectively. On the other hand, nanofiber has a length and a diameter of 100nm and 20nm, where the combination represents a fiber volume fraction of 4%. The length of the nano-debonding of the nano-fiber of 0, 20, 50, 80 and 100 nm is adopted in the study for the cases analyzed, and this value is corresponded to nano-debonding length to the nano-fiber's length L_d/L_{nf}=0, 0.2, 0.5, 0.8. Besides, the nano-fiber and the matrix are to be bonded perfectly except at the nano-debonding line. Representative volume element has a cylindrical shape which consist of a nano-fiber surrounded by polymeric matrix, where a nano-debonding between the nano-fiber and the matrix was considered, as depicted in Figure 2.

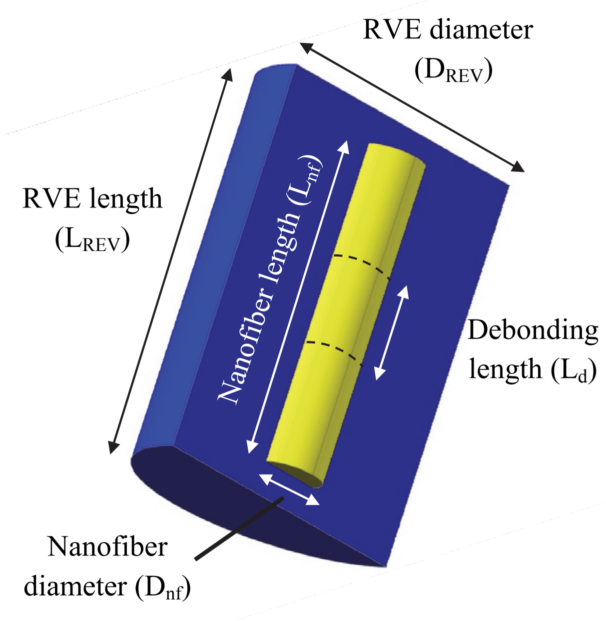

Fig. 2: Details of RVE of nano-composite with interfacial nano-debonding.

Axisymmetric, 3D FEA has been implemented for modeling and to analyze the cases. ANSYS is the software was used, and solid 182 (i.e., four-node quadrilateral element) was considered in the investigation. Figure 3 illustrates finite element mesh used in the analysis for the deteriorated nano-composite with nano-debonding.

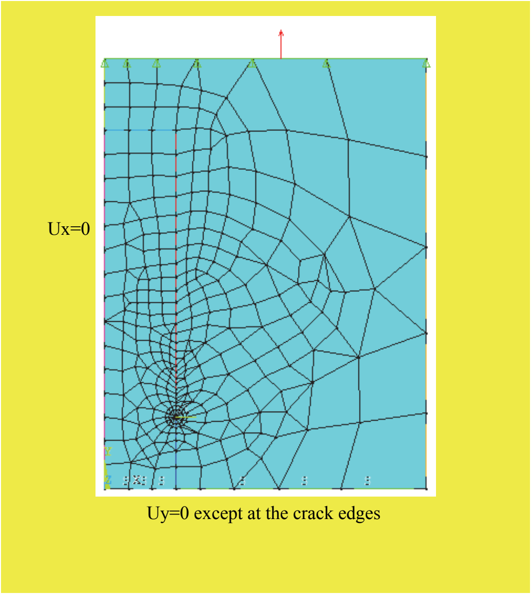

Fig. 3: Finite element mesh for the cracked RVE.

Basically a circumferential sharp crack represents the interfacial nano-debonding in the modeling. A full crack modeling was considered in the analysis, where the a 16 elements surrounding the crack tip were generated in ANSYS to represent the singularity at the crack tip for a radius of 1nm and a radius ratio (i.e., 2nd row/1st row) equal 0.5 with a skewed of 1/4., as shown in Figure 5.

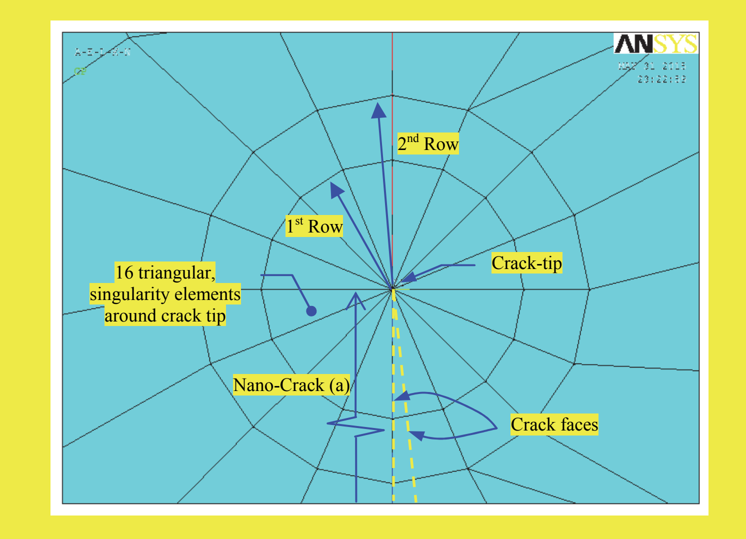

Fig. 4: Used FE mesh around the rack tip.

Except for the nano-debonding line which was left free, basically, tie constraints are applied locally at the interface line between the nanofiber and the matrix, in order to model the interfacial nano-debonding. The detailed no. of nodes and elements used in the present analysis are clarified in Table 1 for the all cases studied.

Table 1: No. of nodes and elements generated for the modeled cases.

L_d/L_{nf}	Nodes	Elements
0 (intact)	117	98
0.2	327	344
0.4	609	631
0.8	866	887
1(full crack length)	1201	1191

3. Results and Discussion

Prediction the effective modulus of the nano-composite through the RVE is the main objective of the analysis to study the impact of this deterioration on the mechanical properties, and how the nano-debonding and the nano-fiber stiffness affects the effective stiffness. In general, there are many techniques used to predict the effective stiffness through using finite element method, one of them is the principle of the elasticity [30] which is mainly used in this analysis to achieve the goal through Hook’s law. Basically, via finite element results, the displacements of nano-composite were estimated and used to predict the effective stiffness but through applying MPC (multiple point constraints) on the edge where the uniaxial load is applied. As a consequence, the effective stiffness of the nano-composite under to uniaxial tensile stress was predicted through the following equations driven from the principle of the elasticity:

$$E_{effective} = \frac{\sigma . L_{REV}}{U_y}$$

Where U_y is the FE axial displacement corresponding to the applied stress. As a matter of fact the reason of using MPC (multiple point constraint) which is adopted in the present FE analysis and is applied on the RVE transverse side where the uniaxial stress is applied, is to maintain a uniform axial displacement of the model and hence to be applicable using Hook's principle. However, it is demonstrated through Figure 5 for intact case, it can be interpreted that as long as the nano-fiber stiffness increases, the RVE stiffness increases, where 6% and 9.9% (with respect to the effective stiffness of E_f/E_m=50) increases in stiffness for the E_f/E_m=100 and 200 respectively. The nano-fiber stiffness enhance the mechanical properties of the nano-fiber in the longitudinal direction and hence increases the effective stiffness of the nano-composite, since the nano-fiber modulus of elasticity is always greater than the matrix. A maximum value of E/E_m can approach up to 1.7 at E_f/E_m=200, which is considered as the greatest level of the stiffness and the reinforcement. Conversely, the RVE stiffness decreases once the nano-debonding length (i.e., crack length) increases, which shows a significant degradation in the stiffness values. The maximum reduction in the stiffness was detected at the fully nano-debonding cases to be 7.5% (E_f/E_m=50) and increases as the nanofiber stiffness ratio increases to be 10% (E_f/E_m=200). Generally, the depreciation in RVE stiffness comes from the crack length in combination with nanofiber stiffness ratio which reduces the RVE stiffness. Moreover, it is clearly observed that for nano-debonding of L_d/L_{nf}=0.2 and 0.5 that almost the nano-composite mechanical properties are the same in term of the effective stiffness, and this reflects that the nano-composite can withstand the deterioration caused by increasing debonding length 2.5 times the basic debonding (i.e., L_d/L_{nf}=0.2). After all, once the debonding approaches 0.8, a clear drop in the effective stiffness started to be seen, whereas the biggest collapse in the stiffness happens at the fully length deponding. Unfortunately this predicted drop in the nano-composite stiffness would have its negative impact in the practical side, where the designers should take this deterioration in their consideration to compensate the lost stiffness through supporting more thickness and hence the reflected consequences on the cost of the material and the manufactured parts.. Eventually, from the present finite that the debonding plays a big role on the reduction of the effective stiffness of the nano-composite, especially along the nano-fibe side. This will emerge a concerns to overcome this issue in the production stages of the nano-composite to avoid any future economic negative .consequences.

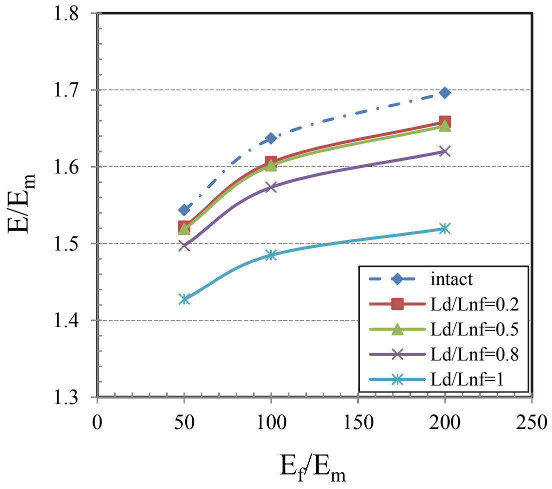

Fig. 5: Nano-composite effective stiffness.

4. Conclusions

It has been observed clearly from the present finite element investigation that the interfacial nano-debonding in a nano-fiber reinforced composite has a significant impact on the mechanical properties of the composite materials, especially the stiffness of the nano-composite. Accordingly, this leads to a serious concerns regarding the economic aspects, since the objective of using nano-fibers to build light structures like renewable energy applications, where the extra material that must be added to compensate the lost stiffness due to internal nano- defects, i.e., nano-debonding. This actually not will impact the dimensions, but also the weight and the cost of the structure, and probably this issue is not studied yet in term of economic consideration for the present time, since the scientist interesting in developing nano-technology, but none of nano-composite is commercialized for bulk structural elements, it will be definitely of major concern.

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