On the Lightweight Structural Design for Electric Road and Railway Vehicles using Fiber Reinforced Polymer Composites – A Review*

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Abstract

The main challenging issues of vehicles with electric propulsion are on the limited energy source due to relatively low battery capacity and low excitation of power traction. They can be tackled down by designing lightweight structures for frameworks and bodies of the vehicles. Composite materials which have a high strength to weight ratio are the best choice for designing and manufacturing the lightweight structures. A review of recent progress in utilization of the composite materials for electric vehicle structures is presented. It focuses on how the structures can support the electric vehicles to compete with internal combustion engine vehicles regarding their performance on the road. The utilization of composite material for structures of railway vehicles is also summarized. Furthermore, discussions are extended to the key technologies required for applying the composite materials in Indonesia such as composite–metal joint technology, fiber and matrix production technology, and numerical analysis competency for modeling the composite.

1   Introduction

Fiber Reinforced Plastic (FRP) composite is one type of composite materials consisting of fibers and matrix [1]. The combination of the fiber that has high strength and stiffness, and the matrix that has lightweight with high fracture toughness produces a novel composite material. The material exhibits the different mechanical properties of its constituents [2]. Modifications of the mechanical properties to the composite are possible by reconstructing the constituent materials. Commercial and widespread composites are carbon or glass fibers reinforced epoxy or polyester matrices. It is commonly used due to its high strength and high toughness of the composite [3]. Furthermore, an eco-friendly composite material such as natural fiber has also been developed. However, controlling the mechanical properties of the natural composite is still a challenging issue [4].

Fiber arrangement in the load directions can also be conducted to design the properties [5, 6]. In fact, the strongest composite can be achieved when the fiber orientation is parallel to the imposed loading direction. Thus, the fiber will effectively carry on the loading subjected to the composite structure. For this particular reason, the design process of the composite structure to determine the fiber directions have to be carefully conducted.

The composite has been widely used as load-bearing structures in engineering industries, such as aircraft, marines, automotive, building construction, etc. [7]. Superiority of having high strength and lightweight is the main advantage of composite material to be used in many mechanical designs. For example, the latest generation of passenger airplanes, such as Airbus 380 and Boeing 787, use composite materials of 25% and 50% of their weight, respectively. Boeing claims that the aircraft can reduce the fuel consumption up to 20%, leading to very significant contribution in tackling the energy crisis [8]. It can also decrease the air pollution caused by exhaust gas of the airplane jet combustion [9].

In automotive and railway industries, the composite usually becomes the first choice in making bodies of those transportations because the complex vehicle profile can be easily manufactured [10]. In automotive industries, complex shapes of bodies are identic with a high-class private car which is touched by fine art. Nevertheless, the utilization of composites for the car body is still not competitive due to unaffordable price

[11]. In railway industries, the complex shapes like streamline structures, especially for a high-speed train, are used to reduce the drag force due to the air resistance or pressure shockwave when the train is going to tunnel [12].

FRP composite has superior properties for designing lightweight structures compared to aluminum-based material. Table 1 shows the basic properties of aluminum (Al), graphite FRP, carbon FRP (CRFP), high tensile (HT) CFRP, and high modulus (HM) CFRP [13]. The unit cost represents raw material and manufacturing costs, such as extruded aluminum or pultruded FRP. Although the cost of FRP composites is higher than the aluminum, particularly CFRP composite having the most expensive among other materials, it is compensated with the strength-to-weight ratio of FRP composite which is higher than aluminum. With identic weight of the aluminum, the composite can prove a higher strength to bear the loading. Thus, lighter structures can be obtained by using the composite.

Table 1   Aluminum and FRP properties comparison [13].

Property	Al	GFRP	HT CFRP	HM CFRP
Fiber content (60%)	-	60	50	50
Elastic modulus, UD FRP (GPa)	70	45/16/5.0	120/15/4.3	200/15/4.4
Poisson's ratio, UD	0.34	0.27	0.22	0.22
Yield stress (MPa)	300/200	-	-	-
Strength (MPa)	-	1100/110	1500/100	1000/110
Density (g/cm^3)	2.7	1.9	1.55	1.65
Strength to weight ratio	111/74	579/58	968/64	606/67
Approx. unit cost	6	15	40	40

2   FRP Composite for Electric Vehicles

2.1   Road vehicles

The worldwide have attempted to reduce CO_2 emission per km by ratifying EURO-6 regulation in 2021 [14]. A high tax will be applied to the vehicles exceeding 95 g/km of CO_2. The regulation makes the automotive industries develop new vehicles to fulfil this rule. However, conventional vehicles using Internal Combustion Engine (ICE) technology as propulsion might not fulfil this regulation. In fact, the ICE technology has matured and reached saturation. The only possible improvement for ICE vehicles is by reducing the weight and drag force of the vehicles. Revolution of automotive industry is predicted to occur in 2025 in which the ICE vehicles will be substituted to

Electric Vehicles (EVs) [15]. In this period, EVs are predicted to have the same cost as the ICE vehicles [16, 17]. Start from 2012, the EV has been operated approximately 60.000 units around the top ten EV countries [18] and by the end of 2016, there were 2 million EVs in the world's road.

Figure 1 shows four step phases of the revolution from ICE vehicles to EVs. There are two types of vehicles as bridging technology of the revolution such as hybrid vehicle and Extended Range EV (EREV). Hybrid vehicle uses both ICE and electric as propulsion. The propulsion can be switched depending on characteristic of the driving. For example, in traffic jam, the electric propulsion brings more beneficial due to its efficiency. However, when the vehicle is in highways, ICE propulsion can be turned on because the vehicle requires more torque and power. Hybrid vehicle has been commercially produced and ready on the market. Additional technology such as regenerative breaking is installed to increase the efficiency of energy consumption.

Unlike the hybrid vehicle, EREV does not use the ICE as propulsion. The propulsion is fully supported by electricity. In the EREV, the ICE remains in the system to charge the battery when the capacity of the battery is low. This can be used to avoid range anxiety of the driver during use the vehicle especially when the charging infrastructure is not ready yet. In case the infrastructure is ready, the ICE can be taken out. Thus, the EREV becomes EV fully.
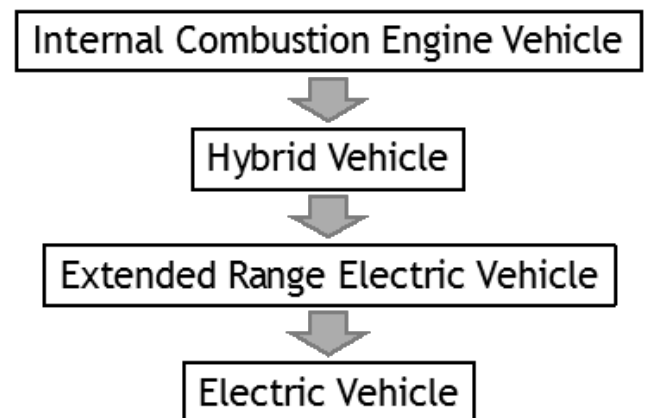

Figure 1   Electric revolution phase from ICE until 2025

Table 2 shows a comparison between the EV and ICE vehicle. EV still has a lower energy saving than ICE vehicles limiting traction and power. The refilling time of the EVs is also considered slow. In current technology, battery charging system is much slower than the oil-fuel vehicle by refilling it to the tank. An idea to integrate the EVs with grid system has been

proposed to reduce the effects of this disadvantage [19]. In contrast, the impact of the EV to the environment is lower than the ICE vehicle because the EV does not emit a carbon emission directly. For energy efficiency, EV is also better than ICE vehicle. Another issue of the EV is cost production which is relatively higher than ICE vehicle. However, it is expected to decrease due to the increasing demand and EV technology development.

Table 2 Comparison between EVs and ICE vehicles

Parameter	EVs	ICE vehicles
Energy saving	Low	High
Energy refilling	Slow	Fast
Environmental impact	Low	High
Energy efficiency	High	Low
Cost production	High	Low

To tackle low energy storage in EVs, the main and substructures of the EV must be created as light as possible. FRP composite can be solution to this problem. In the National Composites Center (NCC) Japan, the CFRP composite technology is used for substituting all component of the vehicle chassis made of aluminum alloy [20]. This substitution was proposed to reduce 10% vehicle weight with the same verified rigidity. Furthermore, the composite is also applied in the critical location that needs a higher strength, such as crash management structure [21], the composite frame rail [22] and the suspension system [23]. In fact, there are many potential metal components that can be substituted by the composite [24, 25].

Another advantage of FRP composite is their manufacturability in which complex shape can be easily created. The complex shape of car body is not only used for eyes catching with fine art but also for significantly reducing a drag coefficient and increase the aerodynamics performance [26, 27]. Figure 2 shows the illustration of the force that acts on the car. Traction force is caused by the grip of a tire on the road and draws the vehicle to move forward. Down force and drag force are aerodynamics consequence of the moving vehicle. These forces are reaction thrusts created by aerodynamics characteristics of a vehicle [28–30]. Together with weight of vehicle and static friction coefficient (μ), the down force determines possible traction achieved by the vehicle.

Figure 3 shows the illustration of the total downward force which is sum of vehicle weight and a down force. Consider a constant μ, higher total force will generate a higher traction. As we design the vehicle using lightweight structures, the possible traction generated by the vehicles will be small because the vehicle wheels cannot grip the road properly. This is not beneficial

especially for high-speed driving. Thus, an additional down force is required in high-speed driving to compensate the loss of vehicle weight.

From the illustration, FRP composite plays an important role to create high performance of the EV [31, 32]. The composite can change proportion of the total force as shown in Figure 4. Without the composite, a vehicle has a heavyweight structure with small down force. This structure requires high traction to accelerate the vehicle, especially under low-speed condition. Thus, high energy consumption for the vehicle is required. In high-speed condition, the body shape generates high drag force which causes the vehicle requires a lot of energy to move and reach maximum speed. In contrast, by using the composite structures, the vehicle has light structures which cause smaller traction is required to accelerate the vehicle in low-speed condition. In high-speed condition, the complex shape of vehicle causes high down force and low drag force. Thus, the vehicle can maneuver easily with keeping the traction to avoid slip condition. As a consequence, the energy required to run the vehicle with the composite structures will be much smaller than without composite structures.
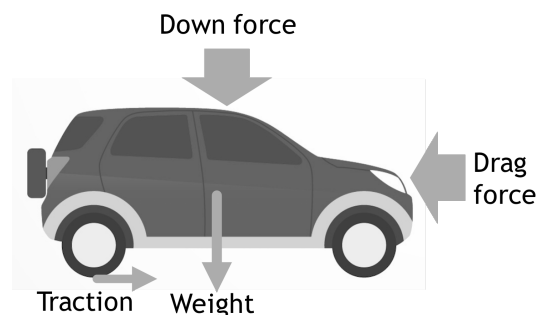

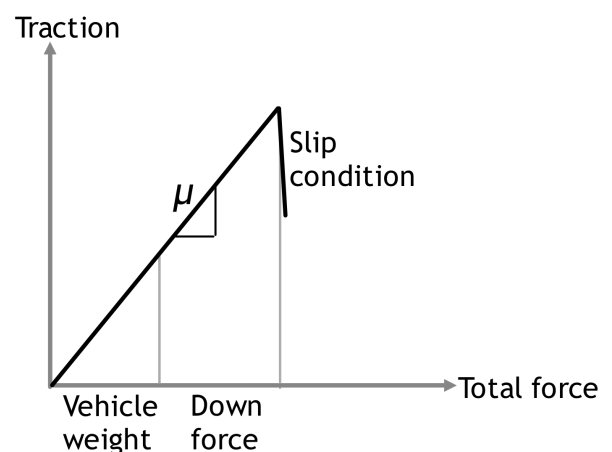**Figure 2** The acting forces on a moving car

Figure 3 Slip condition where the traction decreases significantly by the increasing of the traction
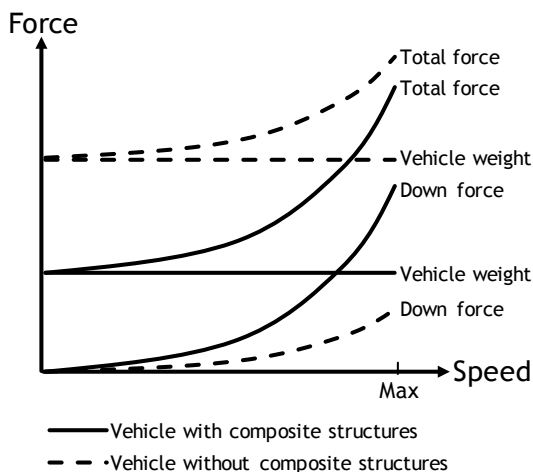
Figure 4 The downward force is the total of the down force and the weight of vehicle

2.2 Railway vehicles

Composite material is firstly applied in railway industry in the 1950s for interior components such as seats, baggage place, toilet features, etc. [33]. The glass FRP is commonly used here. Together with advanced development of the composite, some primary structures were also started to use the composite. Main reasons for the utilization of the composite are due to the increasing performance of speed, energy efficiency, and Noise Vibration and Harshness (NVH) aspects of the vehicle [33]. Tilting Train eXpress (TTX), Automatic Guided Transit, and a Bimodal tram in Korea are example trains applying the composite structures.

The advanced technology of railways technology is designed for a high-speed train. Tokaido Shinkansen line in 1964 is the first vehicle that runs over 200 k/h. TGVA-A noted speed of 300 k/h in 1989. KTX-II in Korea was started in 2007 with the maximum speed of 400 k/h [34]. This high-speed becomes a benefit for a passenger by moving to the destination very quickly. However, it also generates a high resistance of an aerodynamic drag about 75-80% of total resistance [35]. Due to its speed, the safety aspect has become a high concern in developing these trains [36, 37]. A serious problem of an aerodynamic shockwave is one of them. This becomes more serious when the train enters the tunnel. A compressive wave is usually generated at the entrance, then propagates at the tunnel exit. This phenomenon gives high stress to be carried by railway and tunnel structures.

Ku et al. [34] study on optimal cross-sectional area distribution of a high-speed nose. An analytical calculation has been done and applied to the result in the numerical simulation. The optimization for nose length of 5, 7, 10, 12 and 15 m was designed in complex profile. The study aimed to minimize the micro pressure

after a train exit a tunnel by optimizing the nose profile. By the reduction of the shockwave, the vehicle drag also reduces.

In a ballast track tunnel, the pressure gradient is propagated by an energy dissipation of porous ballast. Thus, the compression wave can become smooth. In a short track tunnel, the compression pressure gradient can be neglected. However, Figure 5 shows that in a long track tunnel, the wave-front of the compression wave steepens during propagation through the tunnel due to the non-linear wave characteristics and the after-exit shockwave becomes stronger. The nose shape design is one of the effective countermeasures of this phenomenon. Smooth and streamline nose decreases the pressure gradient of the compression wave at the tunnel entrance and thus, it generates a lower after-exit shockwave.
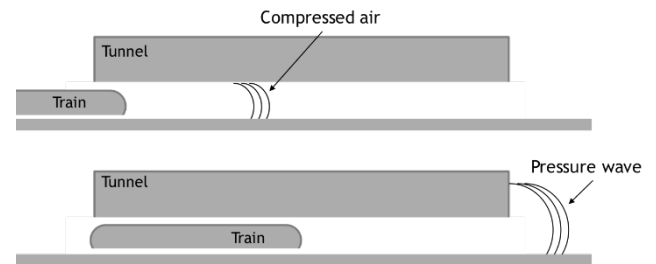

Figure 5 The compression wave and after-exit shockwave

The application of a composite technology can solve the issue. The complex nose profile can be efficiently approached by composite fabrication. The benefits of applying composite material for train nose are cost-efficient and can form the complex profile smoothly and easily than the metal sheet process. Furthermore, the main issue of high resistance force can be reduced by manipulating the vehicle profile into a streamline shape. The reduction of drag force can make the vehicle goes smoother, and the most important is to reduce the energy consumption. Furthermore, the critical loading that occurs in the vehicle also can be carried by the composite structure configuration by its strength and the properties.

Applications of the FRP composite in the rail vehicle design and production are not only on its nose or complex skin manufacturing but also the other mechanical part. It is used certainly due to its lightweight and the mechanical strength. The numerous comprehensive studies also have been done by many numerical or experimental works.

Joint mechanism of bolt joint to integrate the bogie part has been studied by Kim et al. [38]. The study improves the structural integrity by designing the optimum

location of bolt joint for the suspension system. Urban railway trains that have GFRP composite bogie requires a specific treatment on its joint. Numerical study using ANSYS Parametric Design Language that has conducted shows that the excellent analysis of a sub-modelling method can be applied to various structures in the applicable areas without any restriction.

Zinno et al. presented a multiscale approach of experimental, theoretical, and numerical studies of sub-component of the railway vehicle [39]. A composite sandwich roof is considered from benefit of material, manufacturing process and the cycle up. The proposed multiscale procedure showed a good agreement in optimizing design using experimental, numerical, and analytical tools. The material and manufacturing method were also required to design further component such as a flank or other component if the result has proven based on the procedure. The other critical studies have been conducted to prove that the composite material is a reliable material to be applied in the railway vehicle such as a manufacturing effect on the vehicle safety structure [40], the natural frequency of composite bogie frame [41], the structural behavior under critical loading [42], and the dynamics behavior of composite wheel sets of the railway vehicle [43].

3 Key Technologies to Adopt Composite Materials in Indonesia

3.1 Composite–metal joints

Automotive and railway industries in Indonesia usually use metal materials to manufacture both primary and secondary structures. The radical alteration on the use of metal to the composite might cause unbalancing cost production and market. Thus, the introduction of FRP composite in those industries must be started gradually from several possible components. To integrate the composite-based and metal-based components, first technology that must be acquired by industries in Indonesia is joint technology between the composite and metal.

The joining of composite components with metallic components can use adhesive bonding, mechanical fastening, or a combination of both mechanisms [44]. Adhesive bonding is applied for the joining of composites component by bonding the cured component with wet laminates. The advantages of this method are a flat profile in the joining areas, uniformly distributed, and galvanic corrosion isolation. However, the required surface treatment and curing time can increase the production time and energy consumption.

Further, the environment condition such as humidity and temperature become a variable in the curing time.

Mechanical fastening by through-the-thickness reinforcement is introduced over the composite thickness. The primary advantage of this method is reducing the time and cost of production. Before applied the fastener, the drilling process is required. However, the hole of the drilling can be a weakness of fusion zone, fiber damages, and a load interruption that cause a stress concentration [45]. The most common mechanical fastenings are bolts, rivets, clinches, and staples. These disadvantages must be carefully considered in conducting joining process by the mechanical fastening.

3.2 Fiber and matrix productions

The second technology that must be acquired by industries in Indonesia is fiber and matrix productions. At this time, Indonesia through PT DI can create FRP composite panel with fine manufacturing process for airplane structures. The primary manufacturing methods used to produce composites include manual lay-up, automated lay-up, filament winding, spray-up, resin transfer molding and pultrusion [46].

Although most of those manufacturing processes of FRP composite can be conducted by industries in Indonesia, constituent materials such as the fiber and matrix are still imported from other countries. To fulfill large-scale demand of the FRP composite for structural components especially in automotive and railway industries, the upstream industries of the composite must be built. This can increase the profit margin of the composite business and avoid dependency with other countries in supplying the constituent materials.

Figure 6 shows a schematic of the carbon fiber production. Carbon fibers can be made from polyacrylonitrile (PAN) or petroleum Pitch [47, 48]. In the thermoset process, the raw fiber is stretched and heated of about 200-300 °C in air to remove water and other liquid contents. The fiber is then applied the carbonizing process at temperature around 1000 °C for several minutes. In this process, the fiber is heated again in a furnace filled with a non-oxygen gas mixture such as nitrogen to create an inert environment. This process is conducted to remove all other compounds except carbon. Carbonization rate affects the fiber characteristics. The high carbonization rate will defect the carbon fiber. Meanwhile, a low rate will lose much nitrogen at the early stages. Furthermore, a graphitizing process is applied by heating the fiber in the temperature around 3000 °C. This process aims to align the carbon crystal arrangement in the fiber. Thus, the elastic modulus of fiber direction will be high.

After carbonizing and graphitizing, the fibers need surface treatment to give better bonding properties. The fibers are coated electronically to avoid forming tiny surface defects. The common method of composite surface treatment is pulling the fiber through a solution of electrochemical or electrolytic bath. The solutions are sodium hypochlorite or nitric acid. This process is critical to fiber performance because bonding between matrix and carbon fiber is determined. The effect of surface treatment on the carbon fiber performance has been studied comprehensively [49–51]. After the treatment process, sizing process is performed in which the fibers are coated with epoxy to protect them from damage during winding or weaving. The epoxy is selected based on the compatibility of matrix used. Sizing binds filaments to reduce fuzz, improve processability, and increase interfacial shear strength. Finally, the fibers are ready to spin or yarn to product the carbon fiber sheets.
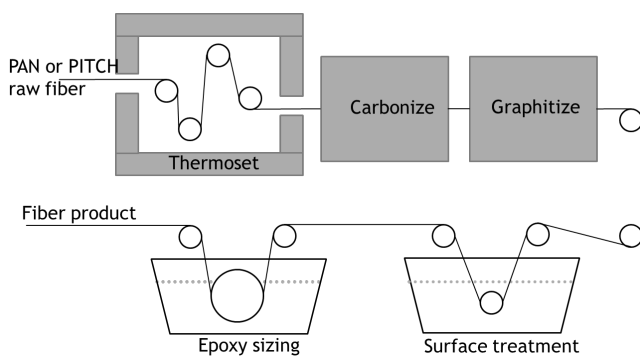

Figure 6 Schematic process of carbon fiber production

Figure 7 shows the suitable parameters for characterizing the surface of fiber. Each process in the fiber production determines the quality of surface characteristics. Wettability and interdiffusion determined by contact angle measurement have a great influence on the mechanical bonding between fiber and matrix [52]. Song et al. studied that the wettability against water and ethylene glycol is improved by increasing the surface roughness of the fibers [53]. Porosity can appear on the fiber surface due to poor sizing process. This can create a void during composite manufacturing process which can drastically reduce the interfacial bonding. Non-destructive and destructive method can be used to evaluate the porosity content of the fiber. Porosity assessing in composites is still in demand because it affects the material strength and lifetime [54]. Furthermore, electrostatic bonding by chemical reaction determines the bonding strength.
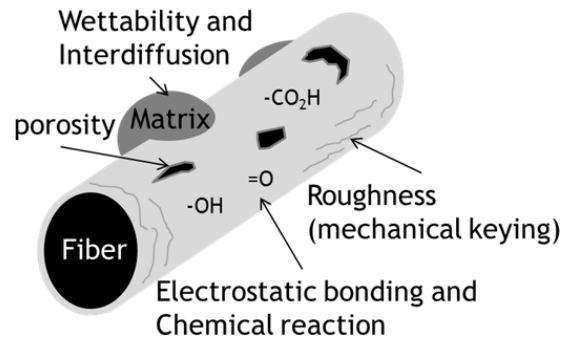

Figure 7 Surface characteristics of fiber

3.3 Numerical analysis of composite

The last technology that is urgently required by industries in Indonesia for applying FRP composite structures is numerical analysis competency. Unlike most of metal materials which have a uniform and isotropic material properties, the behavior of the FRP composite material has a different property in each direction. The composite also has properties which are generated from constituent materials. Thus, a new matter with different properties of the materials is obtained. In term of modeling process, these behaviors require different approach than isotropic material.

The macro-mechanical model of laminated plates is constructed to a lamination theory. It assumes that the laminated panel consists a bonded together of a number of layers [55]. Basically, a layered composite can be modelled as a 2D computational model of multi-layered shells. This method can be divided into the Equivalent Single Layer (ESL) model and Discrete-layer (DL) theory. ESL method models the macro-mechanical properties into a single-layer panel. The weighted mechanical properties of each lamina are determined experimentally and used for the material properties in numerical analysis. DL method is generated to increase the accuracy of multi-layered shell model by considering each layer separately within DL theories. It is also named as the layer-wise formulations.

The effective properties of FRP composite can be approached by using a homogenization technique. The homogenization is an efficient way to determine the macroscopic properties such as the elasticity tensor, conductivity, thermal expansion, and fluid permeability [56]. A valid homogenization can be applied when there is a clear separation between the macro and micro scales. The asymptotic expansion of governing equations allows a separation of scales.

Homogenization theory has explicit assumptions that the fields vary on multiple spatial scales due to the

existence of a microstructure which is spatially periodic [57]. By using this theory, the composite can be replaced by an "equivalent" homogeneous medium. Asymptotic analysis is used to find out the composite properties with the microstructure of fiber and the matrix is considerably very small. Figure 8 shows the illustration of the concept of homogenization. The global material properties can be applied to the uniform medium by defining the heterogeneous medium. Then, the energy functional for the medium and asymptotic expansion is used to generate the macroscopic properties. In addition, the damage modeling of laminated composited has been studied in a comprehensive literature [58]. The damage constitutive is modeled by continuum damage mechanics.

The interfacial strength of the fiber and matrix has been evaluated by a numerical modeling and experiment. An equation of the characteristic length on the stress contour and the interfacial strength was derived [59]. A stress transfer behavior has been investigated by Budiman et al. [60]. The evaluating techniques of the interfacial properties using single fiber surrounding matrix indicate that the distance between fibers should be as close as possible yet no contact should be maintained.
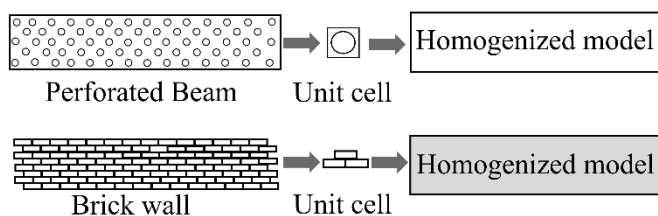

Figure 8 The homogenization concepts commonly used to develop the effective composite material properties

The typical mechanism of composite fabrication is delivered in detail by the numerical study. Mechanical drilling process (including conventional, grinding, vibration-assisted twist drilling, and high-speed drilling) is one example that the machining of a composite is required a special treatment [61]. Drilling operation, drill bit geometry, drilling-induced delamination and its suppressing approaches, thrust force, and tool wear are concerns before executing the composite drilling. A modeling of machining of composite material has been conducted in 2D and 3D Finite Element Method (FEM), molecular dynamic simulations, and the multiscale model [62]. The result shows that some of 3D FEM simulation can model machining process. Chip formation process, tool-particle interaction, prediction of cutting forces, cutting temperature, and the subsurface damage can also be modeled by considering the FEM model of tool geometry and cutting condition.

4   Conclusion

The utilization of FRP composite for EVs has been discussed in this paper. In the automotive industry, the application of composite material will lighten the EV weight and manipulate their aerodynamic characteristics. Thus, it will reduce the fuel consumption. In the railway industry, the aerodynamic resistance of high-speed train can be minimized by manufacturing a streamline and complex train profile. This profile can be formed easily by using composite material. Furthermore, the composite material with high strength-to-weight ratio has been studied to be applied in the critical location of the car and railway vehicle structure.

Three key technologies to adopt composite materials for industries in Indonesia are the composite–metal joints, matrix and fiber production, and finite numerical simulation. These technologies are required to improve the vehicle performance produced by domestic automotive and railway industries. By applying these advanced composite technologies, a lightweight structure with low aerodynamic resistance vehicle is expected to reduce the energy consumption. Moreover, a higher technology level for Indonesian industries can be accomplished.

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