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Development of an Automotive Anti-Roll Bar: A Review

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Abstract – *In this study, understanding between the operation and mechanism of an automotive anti-roll bar is reviewed. Design consideration of the automotive anti-roll bar is studied from past researchers with the summarized of current invention of automotive anti-roll bar. In development of the automotive anti-roll bar, interaction between design elements such as material, function analysis, forces analysis, failure analysis and geometry specifications are essentially need to be considered in development of it without affecting its conventional function and achieve the performance target. The potential of the fibre reinforced composite such as natural fibre is likely to be the next future generation of automotive anti-roll bar. Considerations of the aforementioned design elements would help design engineers to outcome the challenges in design of composite materials. The inventions that patented by the past inventors would help as a guide.*

Keywords: Anti-roll bar, fibre reinforced composite, automotive component design

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1.0 INTRODUCTION

In transportation study, one of the factors of traffic safety is the vehicle (Juan et al., 2014). Vehicle that encounter body roll caused by the driver that lost in handling due to the non-linear response of pneumatic automotive tires and vehicle's body rotates about its longitudinal axis (Kemal Caliskan, 2003). In order to have a better ride quality, there are two important factors that contribute to the stability and comfortability of the vehicle ride which are road condition and proper design of vehicle components (Soliman et al., 2008). However, to control the road condition is not within the area of this study and the only way to improve the ride quality is to improve the design of vehicle components. Particularly, the investigation on the relationship between the linkages and joints in an automotive suspension would lead a way to improve the stability and comfortability of the vehicle (Chen et al., 2012). Automotive suspension consists of guiding elements, forces elements and tires that keep the vehicle in stable and comfort condition. Therefore, in an unfortunate event on the road, the vehicle could roll over because of excessive body roll that caused by the lost in handling.

In automotive suspensions of car; anti-roll bar (ARB) is one of the forces elements that can reduce vibration and keep the tyres in contact with the road. The ARB, also known as the stabiliser bar is a component that is installed in a vehicle to counteract the forces that provoke swaying of the vehicle during operation. There are three types of ARB that are commonly installed in cars: passive, semi-active or active ARB system. The passive ARB system is operated when the ARB interacts with the suspension system passively to minimise vehicle roll at a fixed position. The stiffness of the bar to counteract the torque during the difference in vertical displacement caused by the wheel movement is controlled by the type of material properties and geometry of the bar itself (Carlstedt et al., 2005). Typically, the active and semi active ARB systems consist of a hydraulic pump and hydraulic control. There are also electromechanical active and semi-active ARB systems, which used electrorheological fluid (Barth & Xavier Delayre, 2010). Both the active and semi-active anti-roll system have variable torsion stiffness controlled by an active mechanism. The passive ARB system has a simpler and lower-cost design compared with the active and semi-active ARB system. However, in a test to improve off-road vehicle handling, Cronje and Els (2010) found that that the active ARB minimised the body roll by 55% compared to the passive ARB. They concluded that the active ARB system could improve the handling of off-road vehicles without sacrificing ride comfort. However, for street-legal cars, passive ARB system sufficiently minimises the car's body roll over, and it is economical, easier to install and less complicated compared with active or semi active ARB. Therefore, further study on the suitable materials and geometry of the passive ARB is required.

Through this study, the review on the design and constructions, past inventions and manufacturing process of ARB will be performed in order to study a development of automotive passive ARB that functioned as a mechanism to reduce risk of roll over during particular condition.

2.0 DESIGN AND CONSTRUCTION OF AN AUTOMOTIVE ANTI-ROLL BAR

Particularly, the design of an automotive component requires more understanding of the fundamentals of the product's mechanisms. Lee et al. (2013) proposed a conceptual design process for movement design that mainly concentrates on the functional and movement analysis diagram. This physical principle has dominated the mechanical design requirements for the designers to follow. Automotive components, as mechanical products that are highly technical, require a proper systematic design strategy to achieve the performance target and decision-making process is a priority throughout the design process. For example, material selection process should be performed carefully, as this affects the product properties and design manufacturability. In addition, in the design strategy, it is necessary to identify the forces to which the component is subjected, as these forces affect the component's structure and functions. Moreover, understanding the failure mode of the component would guide designers to the real problems and enhance the design improvement that the component needs. Hence, understanding the function, forces, materials, failure modes and geometric restrictions would guide designers to compute solutions that suit the component without affecting its current good quality (Bhandari, 2010).

2.1 Materials of an Automotive Anti-Roll Bar

The fuel consumption of the vehicle is significantly influenced by the vehicle mass (Tolouei, 2015). Therefore, to produce environmentally friendly vehicle, automakers have an option either to produce a lightweight vehicle to reduce the fuel consumptions or utilize the bio-materials in design of automotive component for sustainability factor. Anti-roll bar is one of the automotive components that have been through redesign process as the material is changed from the traditional steel to fibre reinforced composite materials. The number of materials that been applied for the design of automotive ARB are rising due to advanced research by the past researchers. Moreover, the evaluations of ARB performance are based on stiffness, hardness, fracture toughness and other material properties (Laxminarayan Sidram Kanna et al., 2014; Purohit et al., 2011; Scott & Antonsson, 1998; Sharma et al., 2012; Wittek et al., 2010; Wittek et al., 2011).

Spring steel is one of the materials that are commonly used as a core material in the design of ARBs. Topac et al. (2011) manufactured 50CrV4 (51CrV4) spring steel that is suitable for the design of highly stressed spring. Bharane et al. (2014) found a study from Hubert and Kumar (2005) that explained about ARBs that usually manufactured from SAE Class 550 (G5160 to G6150) and Class 700 (G1065 to G1090) steels. On the other hand, Schulz and Braun (2012) invented an ARB using rope as a core from wound or braided fibres bonded with resin. Besides that, Doody's (2013) research states hybrid carbon fibre could be used as a substitute material for ARBs. However, the shape and size of an ARB should be different from that of a metal-based ARB. Manikandan et al. (2014) performed an experiment on an ARB that made from a round solid steel bar wounded with E-glass/Epoxy. Renner et al. (2014) invented an ARB made from fibre reinforced polymer composite materials. Audi, as a renowned automaker, has developed a hybrid carbon fibre aluminium ARB to reduce the vehicle weight (Scoltock, 2014). Other than carbon and glass fibre reinforced composites used in the manufacture of ARBs, Nadaf and Naniwadekar (2015) performed a study on a nylon ARB and made a comparison between the maximum angular displacement of a mild steel ARB and a nylon ARB. With the recent research into material substitution in the design of ARBs, there could be a great potential for the fibre reinforced composite to be recognised as a suitable material for the ARB.

Due to disadvantages of conventional fibre composite such as carbon and glass fibre that are difficulty to machine, poor recycling properties and potential health hazards, automotive industry has open more options to natural fibre composite to be alternative materials for automotive component (Fan & Njuguna, 2016). However, up till now, natural fibre reinforced composite ARB has not been manufactured yet. However, a study on the natural fibre composite of ARB has been conducted by the author and extensive study should be continued as the natural fibre has a great potential as alternative materials for the ARB for the purpose of weight reduction and sustainability (Mastura et al., 2016). The advantages for having natural fibre composite as alternative material for ARB are lower price, lightweight, bio-degradable and high specific properties (Nabi Saheb & Jog, 1999). There are a few potential natural fibre composites could be alternative materials for the design of ARB such as jute, hemp, kenaf, sugar palm and coir. Natural fibres also have comparable mechanical performance with the synthetic fibres (Koronis et al., 2013). Renowned automakers such as Audi and Mitsubishi Motors have employed natural fibres such as bamboo in the interior components of some of its vehicles (Puglia et al., 2004). Moreover, potential of natural fibre in design of automotive component is studied by Sapuan (2014) where he carried out a study on the application of kenaf fibre composite for shaft.

2.1 Function of an Automotive Anti-Roll Bar

The anti-roll bar is a component that is installed in a vehicle to counteract the forces that provoke swaying of the vehicle during operation. Its function is to generate a reactive force by compressing the suspension on the adjacent side of the vehicle when the suspension on the other side is compressed (Doody, 2013). Basically, the ARB consists of bushings, brackets, bolts and nuts that secure the bar to the chassis to ensure the position of the ARB is aligned with the wheel axle, as shown in Figure 1 (Czaja & Hijawi, 2004). A pair of bushings is constructed with a central bore to hold the bar at the secure position (Hufnagle et al., 2013). Insufficient bushing gripping would affect the roll stiffness of the ARB, meaning that the bar could rotate too easily and move axially and result in a change of its relative position (Gummadi et al., 2003). Therefore, a lot of studies have been conducted by numerous researchers regarding a suitable design for the ARB bushing. This includes inventions focusing on mount bushing, variable rate bushing to control the stiffness of ARB passively and adhesive bushing (Carlstedt et al., 2005; Jang, 2014; Lam, 2012; Suwa et al., 2013). A bracket is used to hold the bushings and is connected to the chassis using bolts and nuts. A summary of the ARB assembly that consists of these components and their functions is shown as the Function Analysis Diagram in Figure 2.

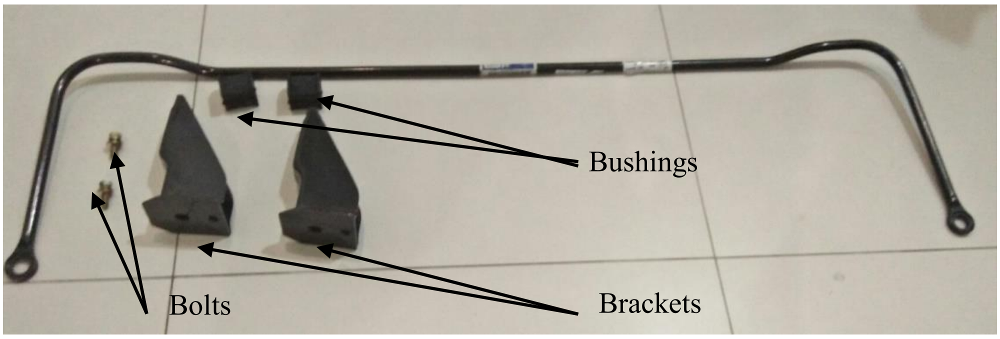

Figure 1: Automotive anti-roll bar and its components

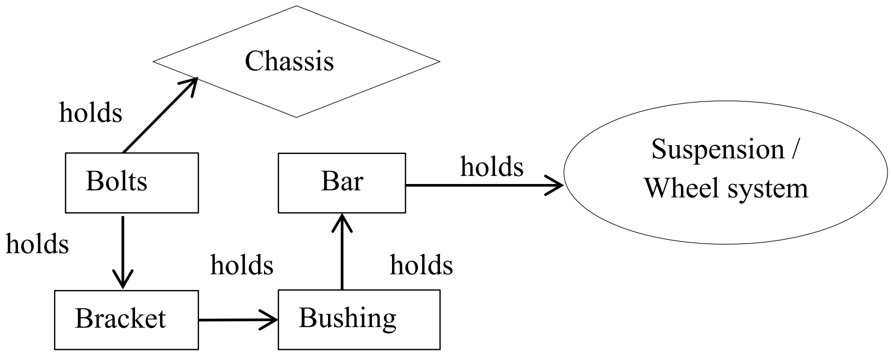

Figure 2: Function analysis diagram of anti-roll bar

2.3 Force Analysis of an Automotive Anti-Roll Bar

When the vehicle wants to turn for cornering or on uneven road conditions, the arm part of the ARB is subjected to the bending load (F). Later, the elbow part of the ARB transfers the bending loading to the bushing area where the loading is transformed into torsional loading (F_A). Here, as many studies performed by past researchers have shown, the elbow part is critical to the design as the part has to overcome extreme mechanical loading that always causes mechanical failure at this location (Liu & Li, 2011; Marzbanrad & Yadollahi, 2012; Shinde & Patnaik, 2013). At the bushing area, the loading is transferred into torsional loading inside the bar (Zhang et al., 2012). The centre area of the ARB is now subjected to pure torsional loading and this causes compression on the other side of the arm (Prawoto et al., 2013).The summary of the force analysis of the ARB is illustrated as in free body diagram in Figure 3. Due to these extreme mechanical loading, critical design process with particular design parameters are importantly to be considered in order to construct a new improved automotive ARB.

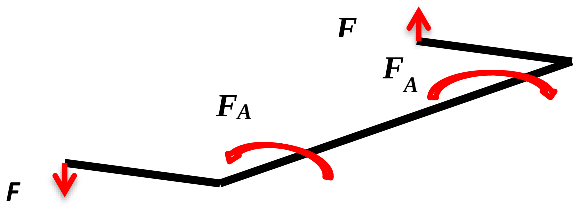

Figure 3: Free-body diagram of anti-roll bar

2.4 Failure Mode of an Automotive Anti-Roll Bar

Any products that perform specific functions from scientific principles and technical information are considered as a machine or mechanical part. This type of products has to encounter mechanical failure before the end of their life. Mechanical failure happens when some parts of the machine are unable to perform its function satisfactorily because of certain condition such as permanently distorted, reliability downgraded or separated into two or more pieces (Budynas & Nisbett, 2009). At this point, root cause analysis has to be done in order to identify the cause of the failure and act of prevention should be taken prior the production of the parts to avoid any repeated failure.

The automotive ARB, as one of the mechanical parts that is installed in an automotive vehicle, is also subjected to mechanical failure that could degrade the whole performance of the vehicle. The ARB has to be stiff enough to resist the torsional loading that occurs when the car is subjected to various forces. As explained previously in the ARB force analysis, if one side of the suspension is moving in opposite directions, the bar is subjected to torsional loading and this reduces the roll angle of the vehicle. Palma and Santos (2001) conducted an experimental study on the fatigue damage of an automotive ARB. From their laboratory and road experiments, they found that a fatigue life of 78,000 cycles can be used as a failure criterion for the ARB. In other research, Bayrakceken et al. (2006) reported that, after travelling a distance of 100,000 km, most of the ARBs had fractured at nearly the same location, which is at the corner bend. Similarly, the fatigue tests conducted by Mao et al. (2012) demonstrated that the cracks arise on the ARB's surface, which is the place for stress concentrations.

Determination of ARB failure modes has to be done before the geometry of the ARB is determined. The geometry of the ARB depends on the operating conditions and the shape of the other adjoining components in the system. Soon et al. (2005) reported that geometrical design parameters such as bar diameter, bushing lateral movement, wall thickness and bend radius should be considered to maximise the fatigue life and the roll stiffness while minimising the weight. Furthermore, the ARB processing method also influences its fatigue life. Colosio et al. (2004) performed a study to investigate the differences in fatigue behaviour between a stabiliser bar manufactured in quenched & tempered steel and normalised SAE5160 steel. They found that the superior performance of the martensitic stabiliser bar in relation to fatigue life could be reduced or lost when a micro-notch is present. Perenda et al. (2015) reported that deep rolling of the ARB could increase its fatigue strength and lifetime. Other than the diameter and manufacturing process of the ARB that influence its fatigue life, the assembly components could also influence its fatigue life. The bushing is one of the components that could significantly control the stiffness of the ARB. Therefore, selecting the design and materials for the bushing would affect the ARB's performance. Several tests have been performed by past researchers. For example, Cerit et al. (2010) performed an investigation into the effect of rubber bushing on stress distribution and fatigue behaviour of an ARB. They found that reduction of equivalent stress in the ARB could be accomplished by modifying the bushing, which provided a significant improvement in the fatigue life. A 9% improvement in the fatigue life with respect to base bushing could be obtained by selecting relatively soft rubber materials.

2.5 Geometry of Anti-Roll Bar

Generally, Luft et al. (2012) stated that, according to the Spring Design Manual (SAE Committee, 1996), calculation of the design parameters of an ARB should be carried out with the assumption that the bar is straight with a uniform cross section and is subjected to torsional loading only. Moreover, for the tubular configuration, the inside and outside diameters should be concentric. It was found that the most conventional ARB style is one constructed with a long U-shaped or C-shaped steel member of circular and constant cross section, as shown in Figure 1. Calculations on the diameter and length of the bar should be performed correctly, because any miscalculation in the value of the proper diameter and length would affect the ARB's mechanical properties, which includes its fatigue life. According to Rill (2012), the stiffness of the ARB is defined by its geometry and material properties and strongly depends on its diameter, as shown in the equation below :

$$c = \frac{G\pi d^4}{32a^2 b} \qquad (1)$$

G is modulus of shear, *a* and *b* are defined as the length of the arm and the body centre respectively, and *d* is the diameter of the ARB. From the equation, the material for an ARB can possibly be changed from the conventional steel to composite materials, especially natural fibre composite. By changing the material, the material properties like modulus of shear would be different and the ARB's design could be improved by increasing its diameter to achieve the desired stiffness. Furthermore, it would also raise the equivalent stress and also the notch effect at the critical regions. Ribeiro and Silveira (2013) performed a study on the influence of geometric variables on the stiffness of an ARB using finite element analysis. They varied the position of the bushings that are used to hold the bar, profile cross section and the angle at the corner bend without changing the weight of the ARB. They concluded that, among all the bar variations analysed, the best stiffness/weight ratio was achieved using the shortest length of the arm.

3.0 INVENTION OF AUTOMOTIVE ANTI-ROLL BAR AND ITS ASSEMBLY

For a traditional design of automotive ARB, invention from Hansson and Fuks (2010) is one of the examples of U-shaped automotive ARB. Hansson and Fuks (2010) invented an ARB for a vehicle that significantly solved the problem related to the displacement of the ARB with regard to the bushings. They found that the problem that occurred during the excessive axial movement of the ARB caused non-symmetrical disposition with respect to the suspension arrangement. In their invention, as shown in Figure 4, the ARB assembly for the suspension arrangement in a vehicle has a different diameter. This ARB has the same bushings, which can be mounted at both the receiving and non-receiving sections. Regarding this, the design could reduce costs, it simplifies the ARB modification, and offers a solution to the aforementioned problem by comprising the receiving means for resilient bushing. Furthermore, axial movement of the ARB during operation could be reduced due to the small amount of vibrations that is allowed in order to reduce the amount of strain on the housing and bushing. However, during normal operation, this arrangement could generate noise as a result of the rubbing action between the rubber bushings and the bar surface. At the bushing area, receiving means and non-receiving means, an adhesive coating should be added in order to provide a strong and durable bond between the steel bar and the resilient bushing.

As invented by Lam (2012) an adhesive coating could hold bushing securely to an outer surface of the bar and fix its position relative to the bar by the body. In addition, in order to ensure the bushings are securely fitted at their position and to prevent transverse displacement, Sterly et al. (2008) invented an ARB assembly with an annular ring that is either formed as an upset or attached to the ARB. In order to accommodate the annular ring, the bushings have a groove on their inner diameter and resist some transverse movement. Moreover, the intermediate bushing invented by Johnson and Jeffrey (2008) has a similar function to the annular ring. However, the intermediate bushing is formed of plastic material such as an injection mouldable polymer that provides a smooth and consistent interface with the resilient bushing. Regarding the bushings, Carlstedt et al. (2005) invented bushing for the ARB that has variable stiffness rates. In order to increase and control the stiffness rate, they invented a bushing that includes at least one void extending along its length, either in a teardrop shape, arc shape or bone shape. When the wheels are cornering, the ARB is axially twisted and the void is compressed, opposing edges of the void come into contact. This condition reduces the ARB's axial twist by increasing the ARB's stiffness. Moreover, the bushing is embedded with a layer of softer material while surrounded by a layer of harder material, which also could increase the stiffness rate of the ARB. If these kinds of bushings were adapted in the previous invention, the performance of the ARB could be enhanced by the function of the bushing assembly.

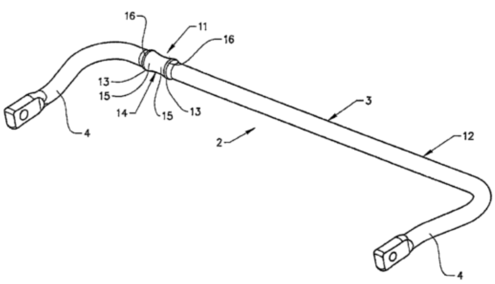

Figure 4: Anti-roll bar according to the invention (Hansson & Fuks, 2010)

Kobayashi (2011) invented an H-type torsion beam rear wheel suspension system with resilient material for the ARB bushing. The ARB of the system is located in the hollow interior of the torsion beam that connects intermediate points of a pair of trailing arms and retains an intermediate part of the ARB to the torsion beam, as shown in Figure 5. This invention could save space and is a highly simple structure. Typically, the conventional ARB system is located separately to the torsion bar and requires bushings that allow excessive movement laterally and axially. Both types of movement would cause undesired vibration, noise and wear due to the contact between the ARB and the outer surface of the torsion bar. Moreover, extra space is needed in the suspension system to locate the torsion bar and ARB clamped together. Furthermore, when handling of the vehicle, during wet road conditions, there is a possibility that water splashing could put pressure upon the ARB bush. This pressure may shift the ARB if it has been designed conventionally. However, through this invention, this particular risk could be reduced. On the other hand, the weight of this structure has not been highlighted in the invention. If the torsion beam and the ARB are clamped together, the resulting structure is more likely to have weight issues during installation in the suspension system. Therefore, it is suggested to change the material in order to reduce the weight of the assembly.

Begenau et al. (2015) invented a lightweight and durable ARB to ensure driving stability of vehicles. Particularly, the main body of the ARB is made of carbon fibre reinforced plastic (CRP) material with highly weight-specific strength and stiffness against torsion as its properties. Daily et al. (2006) in their invention included a composite tube that is suitable for the aforementioned torsion beam. The outer part includes a first fibre layer including glass fibres that have been wound around a mandrel which could be removed after completion of the assembly. A second fibre layer includes glass fibres that have been wound around the first fibre layer, and the outmost fibre layer includes glass fibres that are located around the second fibre layer. The construction of the beam could be formed from many layers of substantially unidirectional fibres.

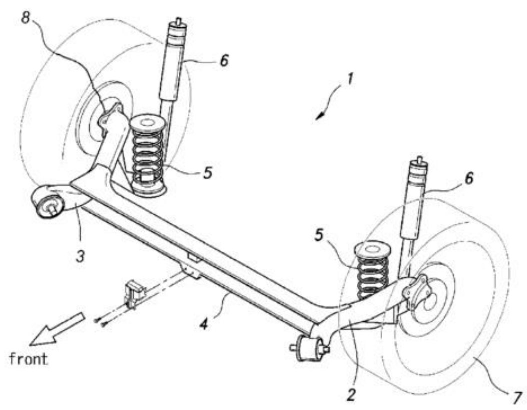

Figure 5: Anti-roll bar system according to the invention (Kobayashi, 2011)

In another design of lightweight ARB, Schulz and Braun (2012) invented an ARB for a motor vehicle that consists of a cord cured with resin in order to achieve stiffness of the bar, as shown in Figure 6. The invention comprised an ARB with bent rotating legs on both sides connected to a wheel suspension of the motor vehicle by the free ends. By using the ropeyards as the preform, laid into a closed tool and infiltrated with resin, the invention reduces the manufacturing cost. The configuration and shape of the invented ARB were left unchanged as the ARB functioned as it was supposed to for a particular type of vehicle. Kleinschmidt et al.

(2014) invented a composite material in the form of a laminated material made of flat superimposed layers that consist of at least one metal layer and at least one layer of fibre reinforced plastic. This construction not only reduces the weight of structural components, especially in automotive application, it could also increase the strength of a component made from composite materials. Thus, at least one layer of metal could be added in the construction of Schulz and Braun's (2012) ARB. Furthermore, the advantages of having a lightweight ARB could also be applied in the suspension system invented by Li and Li (2013). As per their invention, this lightweight ARB would comprise a torsion bar spring connected mutually by a connection mechanism to a vehicle frame through a positioning device. This configuration can improve the anti-roll system by reducing the vibration and prevents the vehicle frame from suffering torsional force during cornering or on uneven road conditions. This could indirectly enhance the life of vehicles. Moreover, bushing should be added in the design of the ARB in order to reduce the risk of displacement during operation. Fader (2001) invented an ARB with bushings that remain fixed to the bar. The bushings securely resist the relative rotary movement between their inner surface and the outer surface of the ARB. The bushings are also moulded directly to the ARB, and this seems applicable for the recent invention by Schulz and Braun (2012). The bushing moulds could be joined together in a ropeyard-based ARB, which would eliminate the drawback of unwanted noise during operation which occurs in the conventional arrangement. Thus, the arrangement and construction method of the ARB could be considered in the development of a hybrid composite ARB.

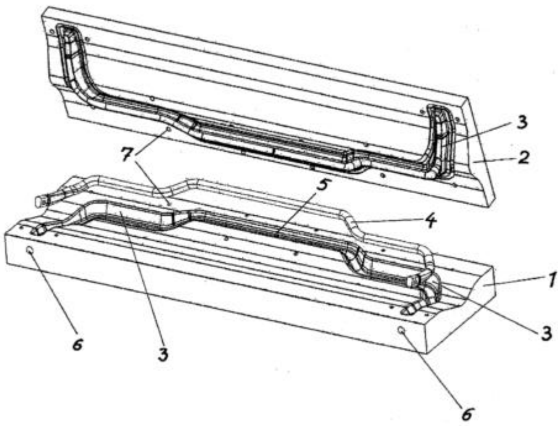

Figure 6: Anti-roll bar for a motor vehicle according to the invention (Schulz & Braun, 2012)

Jung (2011) invented a tapered type of stabiliser bar or ARB with a continuously changing cross section. In the invention, the ARB is constructed with a varied cross section, as shown in Figure 7. The leg of the bar is tapered at each side, from the upper end toward the lower end, and less stress is concentrated at the bent part of the ARB because of the decreased section modulus of the leg bar from the upper end toward the lower end. The loading is distributed over the entire leg bar to prevent fracture failure at the bent part. Moreover, less material is used in order to save costs and reduce the weight of the ARB. In another invention by Jung (2013), the method for this tapered ARB is described as similar to the method presented previously. Both ends of the ARB are heated and rolled so that both side surfaces are tapered. Both portions of the ARB's arm bars have an elliptical cross section that increases in respect of the area towards the bent section of the ARB. This invention has advantages such as being simple to make and cost-effective as the usage of materials and cost of transportation are reduced because the weight of the ARB is reduced. However, Jung's (2011) invention has disadvantages as the ARB may encounter a problem with displacement due to vibration.

Therefore, as invented by Kuroda (2013), it is suggested to include bushing to avoid this displacement. Kuroda (2013) invented a square bracket, a "]" shape, a bushing for fixing the ARB and resin misalignment-preventing member. In addition to preventing bushing from moving along the axial direction of the bar, the misalignment-preventing member that is made of resin is formed outside of the bushing. This invention not only prevents the ARB from dislocating, it also prevents dislocation of the bushing that may become displaced along the axial direction due to vibration. Due to the issue regarding the bend location on the ARB, Anderson et al. (2002) suggested locally pre-heating the ARB immediately prior to formation of the bending section. In their invention, the ARB is locally heated by induction coils or resistance heating at the bend areas. This method could relieve stresses concentrated at the bend areas prior to formation.

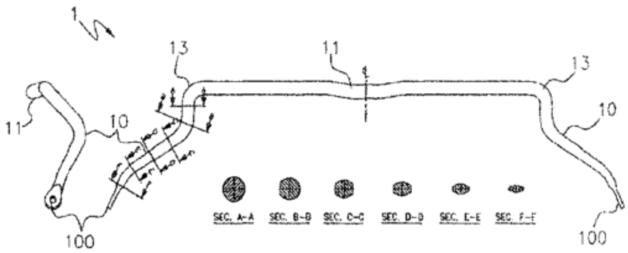

Figure 7: Tapered anti-roll bar according to the invention (Jung, 2011)

Renner et al. (2014) invented an ARB made of fibre reinforced plastic composite, with the method of its manufacture as shown in Figure 8. All the characteristics of the ARB are fulfilled such as cross-section geometry, wall thickness and fibre orientation required by the available construction space and loads to which the ARB is subjected. Different orientations for the fibre are developed for each section of the ARB based on the loading type to which it is subjected, which is adapted in the axial and radial directions to the loads. This construction is to ensure a better force distribution and minimise the risk of failure. Furthermore, ductility of the areas that are strongly subjected to bending forces is increased with a reduction of the wall thickness. In response to the certain expected bending forces at angled end members, the preferred cross section for this area is a circular shape, such as an oval. Milwich et al. (2012) constructed a rod-shaped fibre composite that could be applied to Renner et al.'s (2014) invention, which relates to the construction of a composite material composed of a matrix with a circular braid embedded into it to increase the stability of the composite material. This invention may have stable structural components that are suitable for use in a composite ARB. The stability of the structure is beneficial with respect to flexing and torsional loading in particular, which makes it more appropriate for the development of the ARB. Moreover, in addition to the ARB assembly, a pair of composite ARB links could be installed, as invented by Pulling et al. (2001). The links are connected to each suspension member and have a central body or housing constructed of a polymeric resin including 20 to 40% glass fill for increased mechanical properties. The polymeric housing includes a bowl that is formed at the end of the rod segment. The formation process uses a simple two-piece mould for manufacturing, which reduces lead-time and piece cost. This could be more advantageous for a composite ARB constructed with cost-effective elements. The advantages of having the components incorporated into the composite ARB are: highly durable vehicle stability, highly operable, easy to replace and low in cost. All these combinations from other patents could be incorporated into Renner et al.'s (2014) ARB, which would give a better configuration. The construction of the various characteristics mentioned before would give more ideas about the development of the ARB. The summary of all inventions and suggestions for improvement mentioned here are presented as in Table 1.

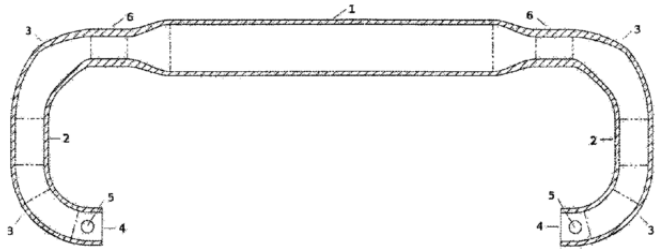

Figure 8: Fibre reinforced plastic composite anti-roll bar according to the invention (Renner et al., 2014)

4.0 MANUFACTURING PROCESS OF ANTI-ROLL BAR

The ARB manufacturing process depends on its material and shape. According to Ashby (2004), the interaction between function, material, shape and manufacturing process is the key in solving mechanical design problems. Function implies the selection of materials and determines the shape, while both of them are subjected to the selection of the manufacturing process. Generally, any type of ARB is designed to resist the roll-over forces during cornering or on uneven road condition, as explained previously. However, the shape of the ARB is different, as it depends on the type of material, manufacturing process and additional function required for a particular type of vehicle.

According to the Society of Automotive Engineers (SAE) handbook (1996), the ARB manufacturing process could be by dye-forging or upsetting process for the particular parts of the bar. However, the aforementioned manufacturing processes are limited to certain types of materials, alloy steel in particular. In Jung's (2013) invention, an ARB that has a continuously changing cross section could be manufactured by heat treatment and rolling. For composite types of materials, the ARB could be manufactured by bladder moulding and filament winding (Daily et al., 2006). The ropeyard ARB invented by Schulz and Braun (2012) was made by a simple manufacturing method where the rope is laid into a closed tool and sealed with resin. Then, resin is pressed into the tool to eliminate air from the preform and saturate the rope laid in it. To improve the performance of the ARB that they invented, during the manufacturing process, a fixing and stabilising agent could be added in the form of powder paint coating, paste paint coating or scatter coating in order to strengthen the ARB's structure, as invented by Hoppe (2013). Milwich et al. (2012) suggested that a rod-shaped fibre composite with high torsional strength and stiffness could be manufactured by a conventional continuous braiding operation.

Table 1: Summary of inventions of automotive anti-roll bar

No	Inventors	Value of Inventions	Advantages	Disadvantages	Improvement for Future Design
1	Hansson & Fuks	The design includes receiving and non-receiving section for bushings to avoid displaced ARB with regards to the bushings.	Costs reduction, simplifies the modification of ARB and invented the solution to displaced ARB with regards to the bushings.	Generate noise that result from rubbing action between the rubber bushings and the bar surface.	Adhesive coating between the steel bar and resilient bushing (Lam, 2012).
					Annular ring which is the bushings provide a groove on their inner diameter that is assembled at bushing area (Sterly et al., 2008).
					An intermediate bushing that made from plastic material (Johnson & Jeffrey, 2008).
					Bushing that having variable stiffness rate (Carlstedt et al., 2005).
2	Kobayashi	H-type torsion beam rear wheel suspension system with resilient material of ARB bushing. The ARB is located in a hollow interior of the torsion beam.	Save space and avoid misalignment.	Weight issue.	The main body of ARB could be made of carbon reinforced plastic material (Begenau et al., 2015).
					Glass fibre composite tube with multi-layer is applicable to reduce weight of ARB (Daily et al., 2006).
3	Schulz & Braun	Composite ARB that consists of cord/ropeyard and cured with resin. The invention composed of ARB with bent rotating legs on both sides and connected to a wheel suspension of the motor vehicle by the free ends.	Reduce cost of the manufacture and amount of effort that needed in production of conventional lightweight carbon fibre reinforced composite ARB.	The configuration and shape of the ARB is left unchanged as the problem on the vibration and unwanted noise during the operation is not solved.	A composite material in the form of a laminated material made of flat superimposed layers that consists of at least one metal layer and at least one layer of fibre reinforced plastic (Kleinschmidt et al., 2014).

					Torsion bar spring that connected mutually by a connection mechanism with a vehicle frame through a positioning device (Li & Li, 2013).
					Bushing should be added in the design of ARB (Fader, 2001).
4	Jung	Tapered type of stabilizer bar or ARB that having continuously changing cross-section. The leg of the bar at both sides is tapered from an upper end toward a lower end.	Continuously changing cross-section of tapered ARB that can reduce failure of ARB. Moreover, less material is used in order to save cost and reduce weight of the ARB.	Displacement due to vibration.	Square bracket, “]” shape, a bushing (Kuroda, 2013).
					The ARB is locally heated by induction coils or resistance heating at the bend areas (Anderson et al., 2002).
5	Renner et al.	Tubular shape with oval cross-section at elbow fibre reinforced plastic composite ARB.	Lightweight.	Low mechanical properties.	Construct the composite material with matrix and circular fibre braid to increase the stability of the composite material (Milwich et al., 2012).
					Composite ARB link that constructed with polymeric resin including 20 to 40% glass filled for better mechanical properties (Pulling et al., 2001).

For a fibre reinforced composite ARB, a different manufacturing process is required. The geometry of the ARB will be different as the material properties are different, as mentioned previously. Some of the automotive components that are used in fibre reinforced composite material instead of conventional materials have been designed with a new shape and geometry. For example, Mansor et al. (2014b) used ribs in their design of a parking brake lever to give additional strength and stiffness to the composite component construction. Generally, the manufacturing process for a composite material is quite different from that for a metal. The manufacturing process for a composite material controls the primary shape and microstructure material attributes of the composite's components, such as the part size, void content and fibre volume fraction, as the properties of the composite are altered to satisfy the performance requirements (Cong & Zhang, 2011). The manufacturing process for a composite material also includes multiple stages, such as an additive process and a curing process (Gutowski, 1997). Moreover, evaluation of the manufacturability of the design should be conducted since it includes interaction between the fibres and resin. It integrates the process constraints with design parameters to measure the suitability of the selected manufacturing process based on design requirements (Tang et al., 2013). Imihezri et al. (2006) performed a manufacturability evaluation by conducting a mould flow analysis for a ribbed composite automotive clutch pedal. An evaluation of the manufacturability of the composite component would also predict any manufacturing defects such as shrinkage and warpage, as performed by Azaman et al. (2013).

5.0 CONCLUSIONS

In conclusion, ARB is known as an automotive component that constructed from solid round steel. Different configurations of ARB could benefit the performance of ARB but some of them are not. Although producing a lighter automotive component is become a trend in automotive industry, but mislead design would cause failure during the operation of the ARB. Furthermore, design evaluation is needed to be done carefully if new material such as natural fibre composite is applied in construction of eco-friendly ARB. With an extreme mechanical loading that subjected to ARB, a lot of design parameters should be considered and evaluated carefully in order to develop a new improved ARB that can functions as it is. Therefore, consideration on the material, function, forces, failure mode, geometry and manufacturing process should be carried out simultaneously without affecting the performance target of the design of ARB. Conventional alloy steel of the ARB could be substituted to fibre reinforced composite material as it has a great potential in automotive industry. Extensive research on the composite materials should be carried out in order to tackle the challenges and shortcomings in producing composite materials for automotive industry.

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