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Evaluating the Crashworthiness of Truck Rear-End Under-Run Bars: A Finite Element Analysis

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ABSTRACT

Rear-end collisions involving trucks can have a direct impact on the safety of vehicle occupants, particularly due to the crashworthiness of the truck's rear-end under-run bar. These types of accidents, which occur between small vehicle and truck, contribute significantly to fatalities and serious injuries, presenting a significant public safety concern. This research paper aims to examine the collision effects on the rear-end under-run bar of a truck and its behaviour when it collides with another vehicle. The study employed the finite element method and simulated the under-run bar and impactor collisions using finite element software. The entire structure of the rear-end under-run bar had been designed, taking into account real parameters. The under-run bar structure was made of steel, and the impactor had a mass of 115kg, which resembled the mass of a motorcycle. A predefined field feature was utilized to apply a velocity of 30km/h to the impactor, which had a cylindrical shape. The element size of the mesh for the under-run bar was determined by using the mesh sensitivity technique. The simulation was tested a few times by using different sizes of elements. It is shown that the force reached a peak value of 28kN at a displacement of 68.25 mm, corresponding to the maximum under-run bar displacement. The data revealed that the energy absorbed increased from time 0.003s to 0.012s, reaching its peak value of 11.08kJ at 0.012s. The results show convincing results and prove the capability of rear-end under-run bar to be simulated and analysed using finite element simulation.

1. Introduction

The number of road crashes that cause injuries and death in Malaysia is one of the highest in ASEAN [1,2]. Most road crashes involve motorcycles which is because motorcycles are less steady and noticeable than other vehicles [3].

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When a motorcycle is involved in an accident with other vehicles such as cars, lorries, and trucks, the motorcyclist will be fatally injured due to the lack of protection of an enclosed vehicle [4]. Figure 1 shows the fatality distribution by type of transport. It is shown that motorcycle contribute the highest fatality among other vehicles.

Collisions between motorcycle and heavy vehicle had been reportedly increased lately. Motorcycle riders frequently cause rear-end collisions by either riding too fast and failing to react when the vehicle in front makes an emergency stop. The most common form of accident between a motorcycle and a truck is a rear-end collision. In Malaysia, motorcycle is picked by the majority of rear-end collisions [6]. When a motorcycle collides with the rear end of another vehicle, the rider has a significant chance of being seriously hurt.

When a motorcycle collides with a truck's rear end, the rider may under-ride the vehicles, making the collision much worse [4]. Therefore, to reduce those potential, engineers created an under-run bar for lorries. The under- run bar is to minimize injuries to the occupants of the smaller vehicle in the case of a rear end collision [7]. The under-run bar will absorb and dissipate a part of the impact energy to minimize the loads towards the motorcycle. The under-run bar will avoid the motorcycle from under riding crash.

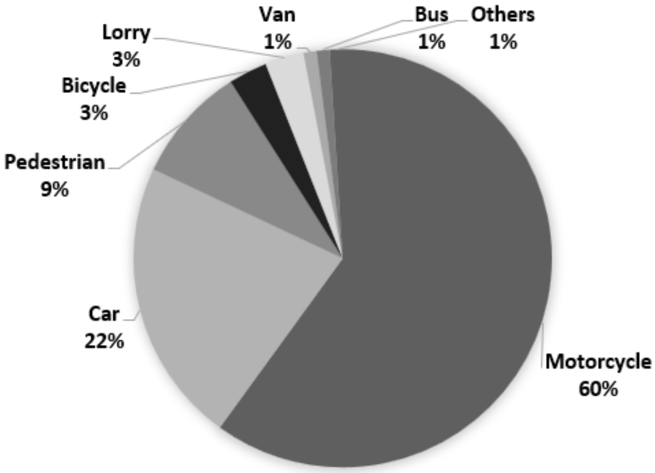

Fig. 1. Fatality distribution by type of transport [5]

An under-run bar is usually installed at the rear end, side and front of a truck. The front under-run bar serves to both deflect force during collisions and stop smaller cars from crashing into the truck from behind. The side under-run bar stops any vehicle or person from crashing into the trucks and being fatally injured. Additionally, the rear end under run bar is utilised to minimise the force of crashes and avoid understeering in car [8,9]. The rear end under run bar also reduces deformation of the car’s passenger compartment when the car crash to the truck rear end [10].

Under run bar is usually made of thin-walled beam [11]. Thin-walled beams are frequently used in crashworthiness applications due to their benefits in terms of light weight, high strength and stiffness, low cost as well as higher energy absorption capacity [12,13]. Thin-walled beams are frequently used in vehicles, such as cars and special-purpose vehicles, as well as roll-over and falling object protective structures and other places where crash safety regulations apply [14,15].

Due to the rise in rear-end collisions between light vehicles and heavy vehicles, a study is necessary to address the issues related to under-run bars [16]. The study aims to investigate the bending behavior of solid beams and assess the energy absorption capabilities of crashworthiness performance during low-velocity impacts. The under-run bar, made of a thin-walled solid beam, will be tested using finite element method to ensure its effectiveness in absorbing impacts when other vehicles collide with it [17,18].

2. Methodology

This study investigated the collision between a motorcycle and a rear-end under-run bar. It examined the boundary conditions on the barrier, the interaction between the motorcycle and the truck's rear-end under-run bar, and the meshing analysis of the truck's rear-end under-run bar geometry and its meshing elements [19-21]. Additionally, the simulation and modeling were crucial components of the study, as they were used to predict the response of the truck's rear-end under-run bar to low-speed impacts.

2.1 Geometry of Rear-End Under-Run Bar

The standard dimensions for the truck's rear-end under-bar were used and the design was selected from previous study by Gidlewski *et al.,* [10]. Figure 2 displayed the model for the simulation. The dimensions were the length, thickness and shape of each part of the under-run bar. The under-run bar was divided into several parts, and each part was designed separately using partition from the finite element software. After designed, the parts were assembled to create a complete rear-end under-run bar. The most critical component of the under-run bar was the beam. The dimensions of the under-run bar beam are 1400mm×40mm×40mm.

2.2 Material Properties and Modelling

In this study, a steel material was selected for constructing both the under-run bar and the impactor. The parameters used to model and define the steel included its ductile damage properties, damage evolution, density, elastic behavior, and plastic behavior. For elastic behavior, elasticity parameters were used, specifically focusing on the Young's modulus to define how the steel deforms under stress within its elastic limit. For plastic behavior, the focus was on yield stress and plastic strain, which describe how the steel deforms permanently after exceeding its yield point. Yield strain data were also taken into account to accurately model the onset of plastic deformation. Detailed data for plastic strain, which describes the material's deformation beyond the elastic region, were provided in Table 1, ensuring comprehensive modeling of the material's response under impact conditions. This detailed characterization of the steel's mechanical properties ensures that the finite element analysis accurately represents the material's behavior during collisions.

Table 1
Material characterisation data for steel

Ductile damage		Yield stress (MPa)	Yield strain
Fracture strain	1	418	0
Stress triaxiality	0	422.18	0.00418
Strain rate	30	426.36	0.00627
Damage evolution	0.02	430.54	0.00836
Mass density(kg/m^3)	7800		
Young’s Modulus (GPa)	210		
Poisson’s ratio	0.3		

2.3 Meshing

The finite element simulation in Figure 2 involves a beam being struck by a cylindrical object, where the beam is supported at two points and meshed with an element size of 10 units. The cylinder is considered a rigid body, meaning it remains undeformed during the impact, simplifying the analysis by focusing on the bar's response. This setup is useful for examining how the bar's material and structure react under dynamic loading conditions, allowing for the identification of stress concentrations, deformation patterns, and potential failure points. The meshes on the beam and the full mesh of the model were presented in Figure 2.

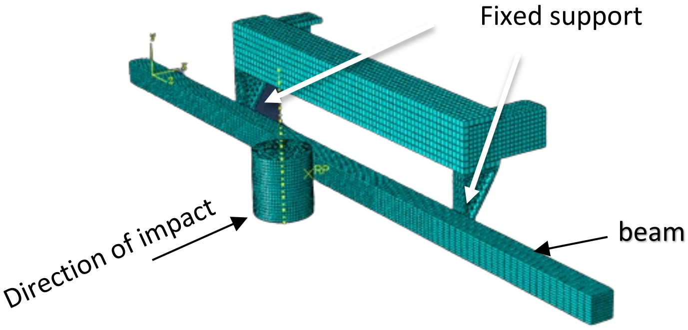

Fig. 2. Full mesh of Model

2.4 Boundary Condition

Figure 2 also illustrates the impactor direction and the model's boundary conditions, which include dynamic explicit and fixed boundary conditions. Both supports are fixed, without displacement allowed in the x, y, or z directions. The cylinder acts as an impactor, moving solely in the x direction. The impactor is assigned a weight of 115kg, approximating the weight of a motorcycle.

2.5 Determination of Energy Absorption

The energy absorption or work done represents the zone underneath the load (kN) versus displacement (mm) graph during the simulation [22-24]. The energy absorption was calculated in the computation until the area before the compaction point occurs, as given by:

$$EA=\int P d\delta \qquad (1)$$

Where P and δ are the applied load (kN) and the incremental displacement (mm) over the deformation process, respectively.

3. Results and Discussion

3.1 Mesh Convergence Study

The parametric studies are a graphical technique used to determine the outcome of a parameter. The validation curve diagram from the parametric studies helped in the selection of the best model parameters [25].

The graph in Figure 3 illustrates the relationship between the number of elements and displacement in a meshing analysis, showing that initial displacements are high (around 95mm). There is a sharp decrease in displacement to approximately 70mm as the number of elements increases to 3, indicating improved accuracy in the model. Beyond 3 elements, the displacement stabilizes, showing minimal variation up to 8 elements, which suggests that the mesh has converged. This stabilization indicates that further refinement beyond 3 elements offers diminishing returns in accuracy, highlighting that an optimal mesh size of around 3 elements balances computational efficiency and result accuracy, making the model reliable without excessive computational cost.

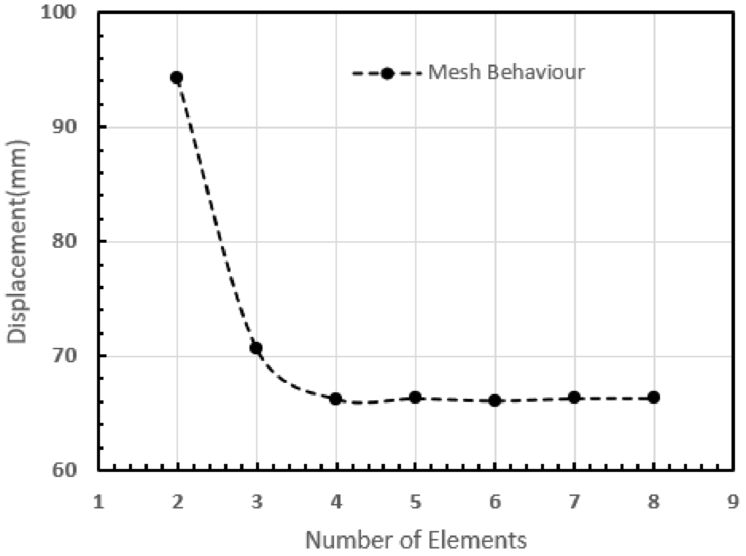

Fig. 3. Validation Curve

3.2 Effect of Collision on Rear-End Under-Run Bar

Figure 4 shows a finite element analysis (FEA) of a steel under-run bar subjected to impact by a cylindrical object provides critical insights into its crashworthiness and energy absorption capabilities. The model utilizes high-strength steel, known for its ductility and energy absorption, with the under-run bar and impactor discretized into finely meshed elements, particularly dense in the impact zone to capture detailed stress and deformation responses. The simulation employs a dynamic explicit solver to handle the rapid impact, with fixed boundary conditions at the bar's ends and a 115kg impactor moving at 30km/h to mimic a realistic collision. The FEA results reveal the stress and strain distributions, showing peak forces and energy absorption during the collision [26]. The deformation pattern indicates how the under-run bar bends to absorb energy, with potential failure modes identified based on stress and strain levels. This analysis allows for optimizing the under-run bar's design, enhancing its ability to protect vehicle occupants by effectively dissipating impact energy and minimizing the risk of severe deformation or failure during rear-end collisions.

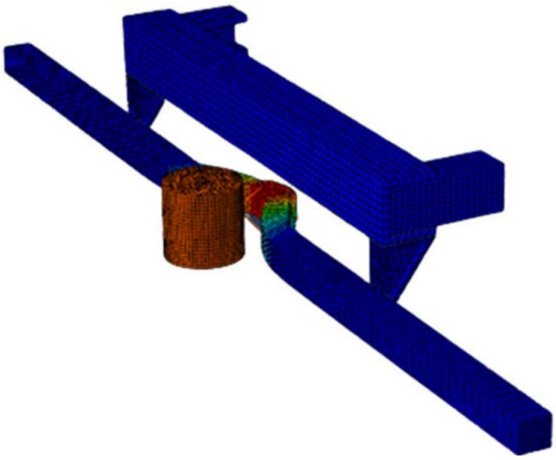

Fig. 4. The Effect of Collision

3.3 Force and Displacement versus Time

Figure 5 illustrates the relationship between force (kN) and displacement (mm) over time (s) during the impact of an under-run bar by another vehicle. At the onset (around 0.003s), both force and displacement begin to rise, marking the initial contact and compression phase where the impactor exerts force on the under-run bar, causing it to displace. The force peaks at approximately 28kN around 0.012s, indicating the maximum stress experienced by the under-run bar. Correspondingly, the displacement increases, peaking slightly earlier and stabilizing around 70mm.

After reaching the peak, the force sharply drops to near zero, suggesting that the under-run bar has effectively absorbed the impact energy, indicating the vehicle has either stopped moving or the force has been completely dissipated. However, the displacement remains stable at around 70mm, indicating some permanent deformation in the bar even after the force diminishes. The force value acting on the under-run bar could be influenced by factors such as impactor mass and velocity. This behaviour highlights the effectiveness of the under-run bar in absorbing impact energy, minimizing the force transmitted to the vehicle occupants, and reducing deformation.

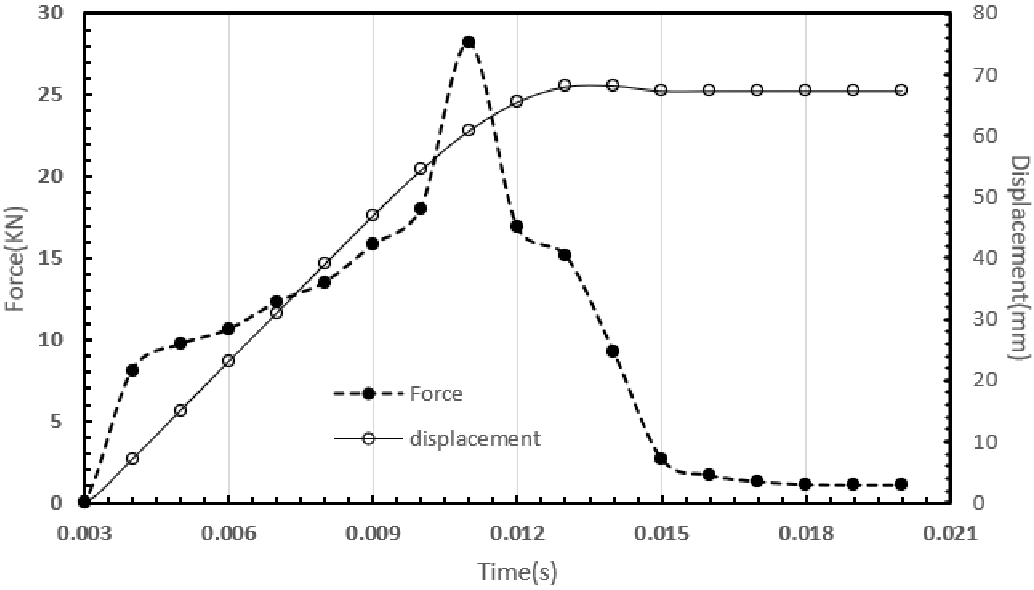

Fig. 5. Force and Displacement versus Time Graph

3.4 Force versus Displacement

Figure 6 showed the graph of force versus displacement. The displacement of the under-run bar could be affected by the force applied to it. From the figure, the force increased until the displacement reaches a maximum value of 60mm at approximately 28kN of force. The impactor then experiences a bounce which at 67mm of displacement, the force began to decrease to almost 0kN. When the force reached its maximum, it indicated that the impactor and the under-run bar were crushed together, and the force decreased as the impactor rebounded and separated from the under-run bar. Even when the impactor is no longer in contact with the under-run bar, the displacement of the under-run bar continued to increase until it reached its maximum displacement. These could due to inelastic behaviour of the target.

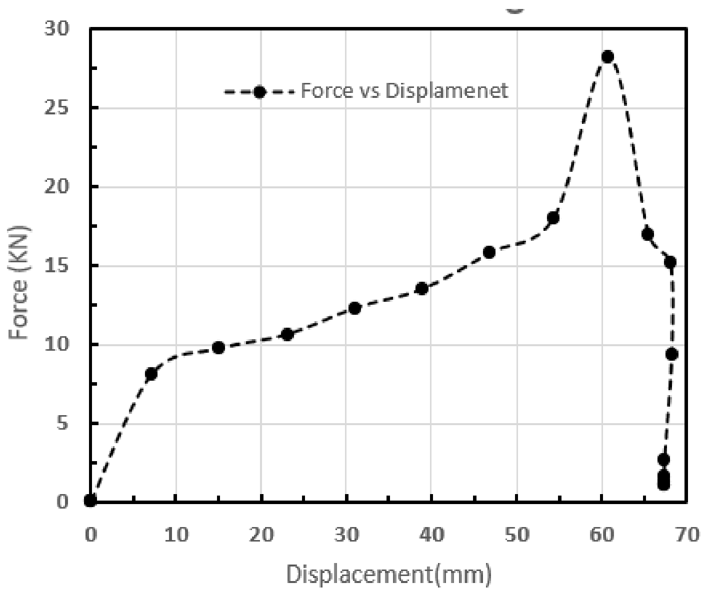

Fig. 6. Force versus Displacement

3.5 Energy Absorption versus Time

The ability of the under-run bar to distribute or absorb energy when subjected to external loads or impacts is referred to as energy absorption. Figure 7 shows the graph representing the amount of energy absorbed by the under-run bar during the collision. The quantity of energy absorbed by the under-run bar increased from 0 to 1780J between time 0.001s and 0.012s. However, the energy absorption decreased from 0.013s to 0.02s. When the under-run bar absorbed energy, it indicated that it could withstand and dissipate the energy delivered by the collision, thereby reducing the risk of damage or failure. Designing an under-run bar with suitable energy absorption capacities was essential in applications where the under-run bar was subjected to impact loads, as it helped protect the vehicle or impacting vehicles from potential danger or damage. By absorbing energy, the under-run bar could help reduce transmitted forces and lessen the chance of failure or severe deformation, contributing to increased safety. The improvement in energy absorption by the under-run bar indicated that the design of the under-run bar could provide a satisfactory performance when colliding with the cylinder and had improved crashworthiness.

The effectiveness of under-run bars in vehicle safety significantly depends on the materials used and the design optimization techniques applied. These factors are crucial in ensuring that under-run bars can absorb and dissipate impact energy effectively, thereby protecting vehicle occupants during collisions. Material selection and design optimization are critical for enhancing the performance of under-run bars in vehicles, ensuring they provide maximum protection during collisions. High-strength steels are often used due to their excellent tensile strength, ductility, and toughness, enabling them to absorb significant amounts of energy while being cost-effective.

In terms of design optimization, the geometry and structural design of the under-run bar play a vital role. Optimizing the shape and incorporating features like crumple zones or honeycomb structures can enhance the bar’s ability to deform in a controlled manner, dissipating impact energy more effectively. Adding reinforcements or ribs to critical areas can improve strength and stiffness without significantly increasing weight. Energy-absorbing features, such as collapsible sections or foams, can further enhance the bar’s performance by reducing the force transmitted during a collision. Finite Element Analysis (FEA) simulations are invaluable in this process, allowing engineers to predict the behaviour of under-run bars under various impact conditions and identify potential areas for improvement. By integrating advanced materials and optimizing design features, under-run bars can provide enhanced safety, reducing the risk of severe deformation and failure during collisions.

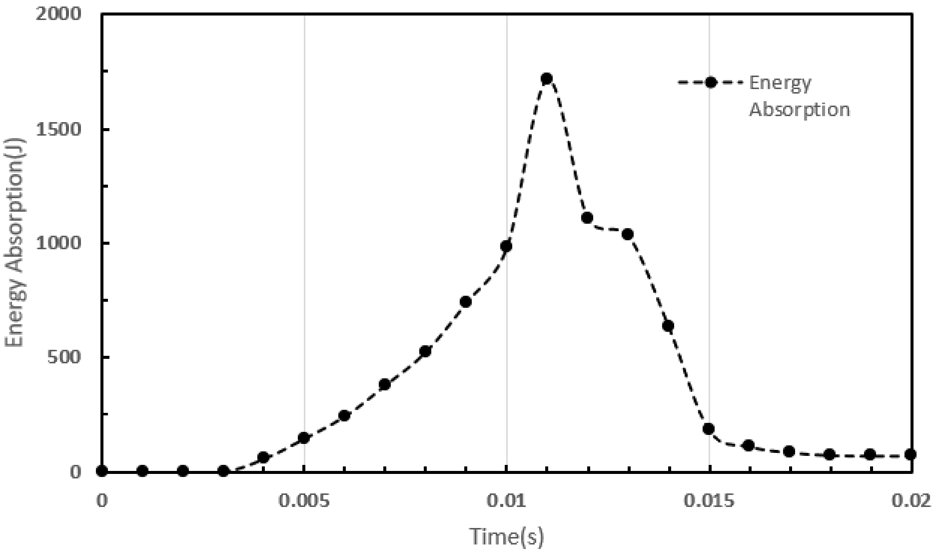

Fig. 7. Energy Absorption Versus Time

4. Conclusions

In conclusion, the study of under-run bars on heavy vehicles, particularly their impact behaviour when struck by smaller vehicles, reveals critical insights into enhancing vehicle safety. Using steel as the primary material for under-run bars, the research employed finite element analysis (FEA) to simulate and evaluate their performance under collision scenarios. The detailed modelling included parameters such as ductile damage, damage evolution, density, elastic behaviour, and plastic behaviour, ensuring a comprehensive understanding of the material's response to impact. The results demonstrated that high-strength steel under-run bars can significantly absorb and dissipate impact energy, reducing the force transmitted to the vehicle occupants and thereby mitigating the risk of severe injuries. The incorporation of advanced materials and optimized design features, such as crumple zones and reinforced sections, further enhanced the crashworthiness of the under-run bars.

By accurately predicting stress and strain distributions, as well as identifying potential failure modes through FEA, the study highlights the importance of material selection and design optimization in developing effective under-run bars. These findings underscore the necessity for continuous improvement and validation against real-world collision data to ensure that under-run bars provide maximum protection during rear-end collisions.

Ultimately, the research confirms that well-designed under-run bars can play a pivotal role in enhancing road safety, protecting both the occupants of heavy vehicles and the smaller vehicles involved in collisions. Future work should focus on further material innovations and refining design techniques to improve the performance and reliability of under-run bars in diverse collision scenarios.

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