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Article

Crashworthiness Analysis to Evaluate the Performance of TDM-Shielded Street Poles Using FEA

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Abstract: The mitigation of the risks of passenger injuries when a vehicle is involved in a collision with a street pole shielded with a layer of tire-derived material (TDM) was assessed. This can effectively absorb a fraction of the total energy from a speeding vehicle. Since such tests are expensive to conduct experimentally, the study relies on using the Abaqus/Explicit FEA solver to accurately calculate the non-linear nature of this scenario. Two categories of this scenario were evaluated to understand the effect a shielded street pole has on the vehicle—and the total absorbed energies during frontal and corner collisions, which are typically the most common categories of such accidents to happen. Results show that at lower speeds, these reinforcements are least effective in absorbing some of the kinetic energy applied by the vehicle, with about 5% of the energy absorbed by the reinforcement. At higher speeds, however, the results show that the TDM reinforcement absorbs about 28% of kinetic energy, which can reduce injury of the vehicle occupants, as well as decrease the damage on poles. Results for this simulation also show that there is a critical thickness of TDM that can absorb these kinetic energies, after which further thicknesses results in energies being applied back to the vehicle, therefore negating any purpose to further increase TDM thicknesses.

Keywords: crashworthiness; light column analysis; finite element modelling; tire-derived material; simulation; street poles

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1. Introduction

Gulf Cooperation Council (GCC) countries, such as Kuwait, currently face a high risk of injuries and possibly fatalities of passengers caused by a vehicle-to-street pole collision, as well as a tire landfill crisis. This research is a continuation of previous research conducted by Alardhi et al. [1], where the initial study was performed to analyze the impact energies of vehicles to naked- street pole crashes for both the vehicle and the street pole, as well as the specific energy absorption (SEA) of the street pole's material. The research was conducted using two materials of street poles, steel, and aluminum, to record the SEA of these materials during a vehicle-to-street pole collision. The results concluded that aluminum generally had better absorption capabilities than steel. Hence steel based street poles would redirect more energy back to the vehicle, therefore, increasing the risk to the safety of passengers during such scenarios. This study is intended to analyze the requirement of shielding needed on steel-based street poles to reduce the overall absorption of the vehicle-redirected energy from the street pole. This shielding is expected to decrease the risk of injury to passengers during a collision, as well as reduce the risk of damage to the street pole.

The initial problem, according to previous studies conducted by [1–4], summaries that the absorbed energy of the vehicles is usually high due to concentrated forces by narrow objects, such as trees and street poles. This issue not only causes damage to the street pole and vehicle but also increases the risks of passengers suffering injuries or even fatalities. According to Federal Competitiveness and Statistics Centre [5], these categories of collisions contribute to a high number of accidents in the UAE. Therefore, innovations to mitigate serious incidents, such as injuries and even death, are essential. Furthermore, while there is various research on such improvements and innovation, as highlighted by other researchers [6–8], these tend to be expensive and unpractical options. However, the study of shielding street poles with recycled TDM can potentially mitigate the impact energies absorbed by both the vehicle and the street pole, as well as achieve the above-mentioned objectives. This alternative option can be useful for developing nations to implement.

Tire-derived material is assessed as a potential material for street pole shielding because it is readily available. According to Ferdous et al. [9], there are about 17 million tons of discarded tires globally, and about 75% of them end up being discarded without any potential for recycling. Some of the currently proposed solutions also bear a huge risk to the environment and public health of local communities, as reported in a case study by Singh et al. [10] on the recent fire caused by the combustion of scrap tires. The actual number of solutions to this issue currently remains low. While there are ongoing efforts to increase the applicability of recycled TDM, such as using them as scrap reinforcements for concrete to increase its tensile properties, as demonstrated by Xu et al. [11] or as a form of composite [12], further local innovations are necessary. Middle Eastern countries, for instance, can find significant benefits in setting up infrastructures to recycle the current discarded tires in landfills and turn them into tire-derived material to use locally as well as to export globally.

Since the experimentation of vehicle street pole collision is expensive to conduct due to the number of tests required to make sufficient assessments and feasibility, research through alternative methods, such as virtually simulating these scenarios, is recommended. Therefore, this paper highlights how the Abaqus/Explicit FEA solver [13] is used to simulate these scenarios instead of achieving quantitative results. Key factors studied in this paper include the reduction of internal energy absorbed by the vehicle and street pole due to the presence of TDM reinforcement and the optimal thickness ranges of these reinforcements to have substantial performance on mitigation of internal energy onto the vehicle during a collision. Therefore, after a thorough analysis of literature sources and past data relative to this study, the following aims are to be achieved in this paper:

- To justify the use of discarded tires as a source to manufacture shielding for street poles through simulation of their function.
- To highlight the reduction of the risk of injury to the passenger by implanting TDM-based reinforcements on street poles.

The above-mentioned aims will be subsequently achieved by studying, assessing, and finally achieving the following objectives:

- The impact energies were mitigated on the street pole and vehicle due to the presence of TDM shielding.
- An initial study on the optimal thickness of the street pole shielding is required to have maximum mitigation of impact energy for both the vehicle and the street pole.
- A study on the variation of the vehicle's velocities and its influence on the TDM shielding's mitigation of impact energy.

2. Literature Review

2.1. Constitutive Equations of Explicit Dynamics

The constitutive equation of the finite element solver is identical to the ones analyzed in the study presented by Alardhi et al. [1], which was based on the study performed by Deb [14] on the calculation of absorbed energy of a vehicle during the crashworthiness analysis of a vehicle to street pole due to the impact force. This is calculated using Equation (1):

$$E_a = F \times d = (Ma) \times d \tag{1}$$

where E_a is the absorbed energy, F is the impact force and d is the maximum plastic deformation. As reiterated by Deb [14], the derivation will lead to the equation eventually becoming an implicit function $F(x(t))$ (where t is time and x is the displacement), which requires to be transformed to a geometric function, $F(x)$. This was performed in the study presented by Sun et al. [15], where the eventual integral equation of the impact energy is derived as seen in Equation (2):

$$E_a = \int_0^d F(x)dx \tag{2}$$

2.2. Constitutive Equations of Hyperelastic Materials

To model the hyperelastic TDM, literature sourcing was essential to justify the necessity of such shielding onto a street pole. The selected material for the model is based on the study of the tensile behavior of TDM using ASTM standard [16] conducted by Montella et al. [17] on four different types of TDMs tested: 500, 600, B800 and G800. Due to the additional readiness of data for the model, it was decided to extract the data of the 500 hyperelastic tire and perform a material calibration. The material calibration is based on the robust yet stable Marlow model. The constitutive equation governing the Marlow model, according to Dassault Systems [18], is defined as shown in Equation (3):

$$U = U_{dev}\left(\bar{I}_1\right) + U_{vol}(J_{el}) \tag{3}$$

where U is the strain energy per unit of a reference volume, with U_{dev} as the deviatoric part and U_{vol} as the volumetric part. $\bar{I}_1$, which is a first deviatoric strain invariant, is defined using Equation (4):

$$\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2 \tag{4}$$

where $\bar{\lambda}_i = J^{-\frac{1}{3}}\lambda_i$, J is the total volume ratio, J_{el} is the elastic volume ratio, and λ_i are the principal stretches. Furthermore, Figure 1 shows the uniaxial tensile tests performed by Montella et al. [17] on the four TDM models that have been tested. These test data were then extracted using the Marlow Model in the Abaqus Material Calibrator to obtain the Marlow constants for the non-linear hyperelastic model to be declared on the geometry of the TDM shield. The first reason why the hyperelastic TDM 500 was chosen is because of its weight, as the density of the elastomer is only 500 kg/m^3. This makes it easier to transport and less expensive to deploy on many street poles. Another reason is that the composition of TDM 500 contains more discarded tire material in the form of Styrene Butadiene Rubber (SBR) than other discarded industrial rubber in the form of Ethylene-Propylene Diene Monomer (EPDM), as explained by Montella et al.

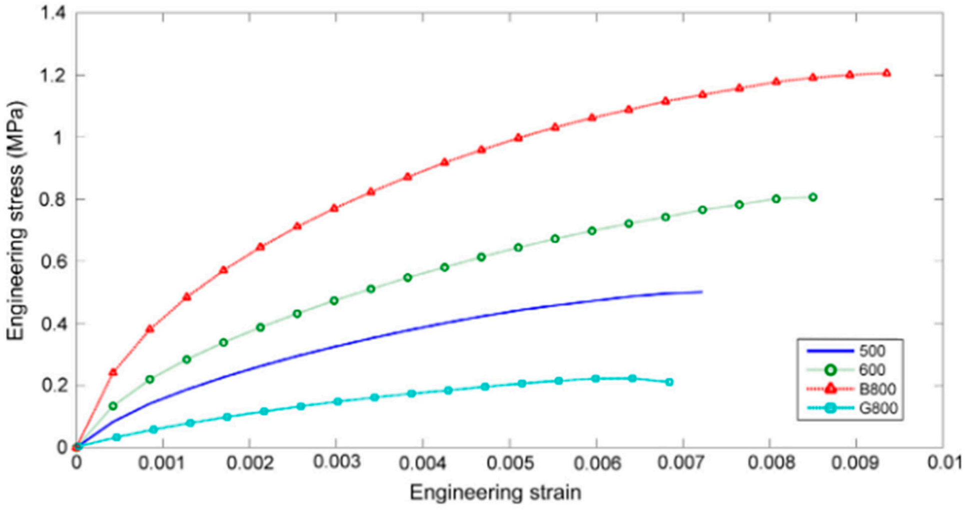


Figure 1. Uniaxial tension test of stress vs. strain of the four variants of TDM [17].

While the B800 variant of the TDM was much stiffer than the 500 variants of the elastomer, it was much heavier with a density of 800 kg/m^3 and required additional manufacturing requirements in comparison to the TDM 500 variant, according to Montella et al. Therefore, the B800 variant might be costly for consideration in this study.

3. Methodology

3.1. 3D Model of the Vehicle

The CAD models of the vehicle's hood, body, and wheels were conserved as conducted in the previous FEA study performed by Alardhi et al. [1]. This means that the overall dimension of the vehicle remains at 1.25 m × 1.41 m × 0.48 m in length, width, and height, respectively. To ensure that the whole car's momentum is applied to the partial model for the simulation, a mass point of 900 kg was added to the already 600 kg of existing mass present in the car's assembly. The mass point was added at the rear end of the lumped interior model. With this, the consistency of simulations between a pure vehicle-street pole collision and a vehicle-shielded street pole collision is conserved. The models were generated using the Generative Shape Design modeler in CATIA V5-6R2020 as a shell model. The "shell" model was assigned to the vehicle's hood as the R_{min}/t ratio is greater than 20, which satisfies thin shell mechanics in Abaqus. For ease of modeling, only half the shell was designed, with the other half generated using the symmetry option, as stated in the previous research [1].

On the other hand, the engine components and the wheel were designed as solids. As explained previously [1], this was performed to represent the 'rigidity' effect of the vehicle to extract relevant results in comparison to a bare vehicle collision without any inertial or rigidity effects.

Other assumptions regarding the vehicle's geometry and structure will be further clarified in the following section.

3.2. 3D Model of the Street Pole

Like the operations performed on the vehicle, the street pole's geometry is also conserved, as conducted by the previous research [1]. Therefore, the street pole's dimensions are as follows; the total height of the street pole is 22 m, the diameter spans to about 250 mm, and the thickness of the street pole's shell is about 5.5 mm. The only obvious inclusion of the street pole is the TDM-based reinforcements surrounding the outer diameter of the street pole's geometry. To analyze the effect of the reinforcement's thickness on the absorbed impact energies, four thicknesses were used; 15 mm, 25 mm, 35 mm and 45 mm. The internal energies for a street pole being collided by a vehicle under fixed boundary conditions should be expected to be around 20 MJ.

3.3. FEA Model

The FEA models simulated in these tests are the front collision and corner collisions against the shielded street pole. Abaqus/Explicit is used for this collision due to the severe forms of nonlinearities present in this problem. One factor includes the instantaneous contact between the high-speed vehicle and the street pole shell due to the collision, which is usually difficult for Abaqus/Standard to converge. Moreover, non-linear material behaviors, such as metal plasticity and ductile damage, have been added onto the street pole and vehicle's geometry for a realistic transfer of energy between the two bodies. Other forms of non-linearity, such as geometric non-linearity, have been included using the NLGEOM function in Abaqus. The material for the vehicle's exterior body, engine body and tire is the same as the one conducted in [1], which is Aluminium-6061. The street pole considered in this study, however, will only be the one made from Steel ASTM A36. The properties of these metals can be found in Tables 1 and 2. Furthermore, the stress-strain profile used to extract the plastic data of these alloys is also the same as the values used in [1]. The reason why this specific material was chosen is that the results shown by Alardhi et al. [1] concluded that the steel poles had lesser SEA than the Aluninium-5052-

based street pole, which meant that the impact energy absorbed by the vehicle during the crash would increase and would cause more risk to the passengers onboard the vehicle. Another reason was also that the aluminum street poles had their structure severed from the base while the vehicle was still in motion. In contrast, the steel pole decelerated the vehicle to a halt. This means that the energy will increase throughout the course of the deceleration. This overall increase, therefore, must be mitigated using a layer of TDM.

Table 1. Mechanical Elasticity and Density Properties of the aluminum alloys and steel grade used in this paper. The values are the same as the ones that were simulated in [1].

Material	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Density [kgm^{-3}]
Aluminium-5052	68.9	0.33	140	2690
Aluminium-6061	69.5	0.33	220	2780
Steel ASTM A36	210	0.29	247.5	7869

Table 2. Fracture values of the metals used in the paper as was done in [1].

Material	Fracture Strain	Displacement after Fracture [m]
Aluminium-5052	0.105	0.002625
Aluminium-6061	0.061	0.001525
Steel ASTM A36	0.24	0.006

Moreover, the reinforcements are geometrically and sectionally modeled as solid continuum elements. This decision was made because the thickness-to-length ratio exceeded the ratio for the street pole to be considered as a thin shell. The solid elements are of the type C3D8R, which means they are 3D stress elements for explicit analysis. The R signifies that the elements have reduced orders of integrations. Furthermore, enhanced hourglass control was declared to avoid results accuracy losses and maintain analysis stability. Finally, since the visualization of the degradation is not critical, element deletion of the reinforcement was enabled while the degradation of the elements was set at 0.8. To optimally chose the correct element size without compromising on the computation time, the global size of the elements for the TDM-based reinforcements on the street pole was set at 10 mm. Sensitivity analysis for the pole and vehicle was already covered extensively in [1]. Furthermore, no further sensitivity analysis was performed on the vehicle and pole to ensure that results extracted from the paper's simulations would be valid when compared to simulations using the same number of mesh presented in [1]. Mesh sensitivity analysis was, however, performed on the pole reinforcement. Three tests were taken with element sizes of 10 mm (50,000 elements), 20 mm (27,000 elements) and 30 mm (23,500 elements). Since the pole did not contain material with plastic properties, the only means of understanding sensitivity was using the deformation results of the three simulations.

A probe was added to the center of impact of the reinforced shield. This is done as the contact between the vehicle, and the shield would contain many sources of contact. These contacts would be highly sensitive to the results; therefore, refinement is required in these critical regions to ensure convergence of results is maintained. As seen in Figure 2, convergence is fairly satisfied after 30,000 elements. Therefore, the simulation included the shield with 10 mm of element sizing to extract reliable results. Therefore, the total number of mesh cells used in this simulation equaled to approximately 60,000 elements.

Finally, the model, as shown in Figure 3, visualizes the final assembly of the impact crash setup to be simulated using the Abaqus/Explicit solver. The impact analysis will be performed both using frontal and corner crash procedures as similarly conducted by Alardhi et al. [1]. The first set of FEA simulations will analyze the thickness of the TDM required to make sufficient mitigations of the impact energy absorbed by both the vehicle and the street pole. The thickness of the TDM shielding will therefore be parameterized according to the thicknesses stated in the previous section to satisfy this objective. The second set of simulations will be conducted to analyze the variation of velocity of the vehicle and its impact on the mitigation of energy absorption that the TDM layer will provide. The vehicle speeds used in this study are 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}, which are identical to those used in the study [1].

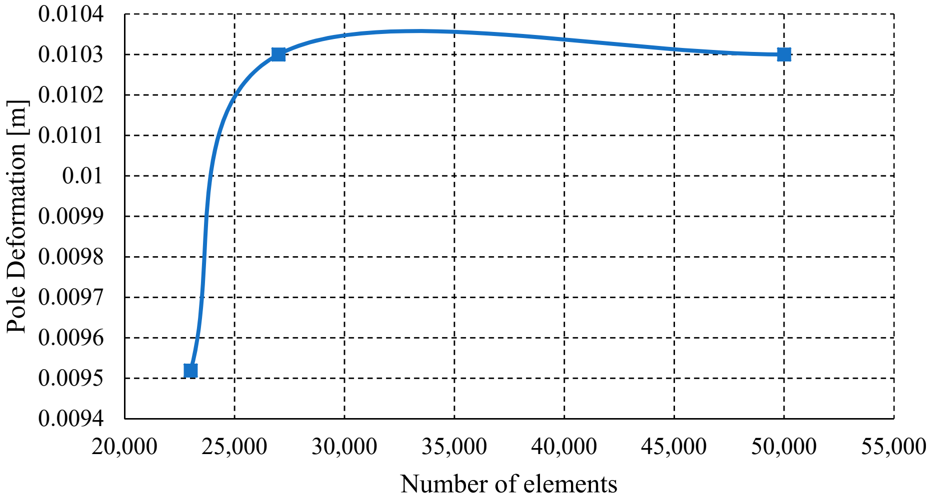
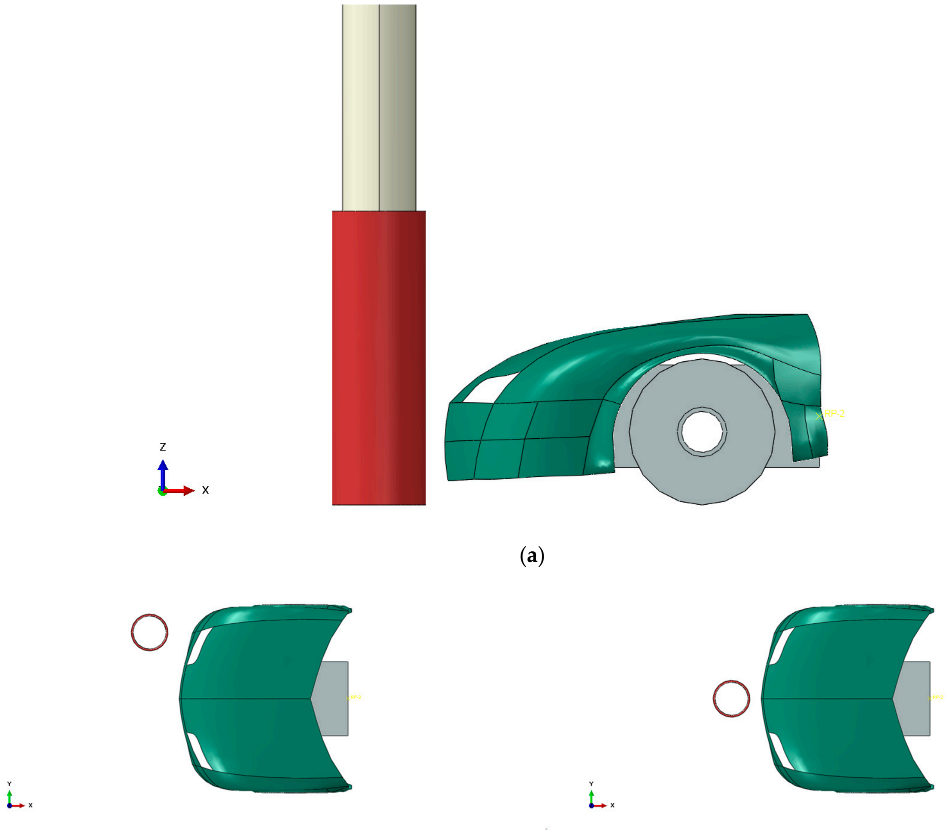


Figure 2. Sensitivity analysis of Reinforced TDM Pole Mesh tested using 23,500 elements, 27,000 elements and 50,000 elements.



(**a**)

(**b**) (**c**)

Figure 3. Model setup of the (**a**) vehicle colliding against a TDM-shielded steel street pole with supporting top views to observe the (**b**) corner collision and (**c**) frontal collision scenarios.

Some assumptions in the FEA model were also considered during this study. Firstly, to compensate for the full mass of the vehicle, a point mass was declared. This point mass is a numerical representation of the entire vehicle to compensate for the missing kinetic energy, as the model lacks the middle and rear body, as well as its respective components, such as the rear wheel, windows, and axles. Furthermore, the stiffness of the overall vehicle is important as well. Since the FEA model was missing key elements presented in the previous statements, the engine was therefore modeled as a complete solid to compensate for this. Moreover, the tires of the vehicle and the front axle were also modeled to introduce further rigidity to the FEA model. Finally, to avoid further complexities in contact analysis for the FEA model, the front of the vehicle's shell was modeled as a single continuous sheet of aluminum rather than individual components.

Additional assumptions, such as the interaction between the vehicle and the street pole, were modeled using frictionless interaction properties because it is expected that there will be many self-contacts during the analysis, as well as contact between many materials.

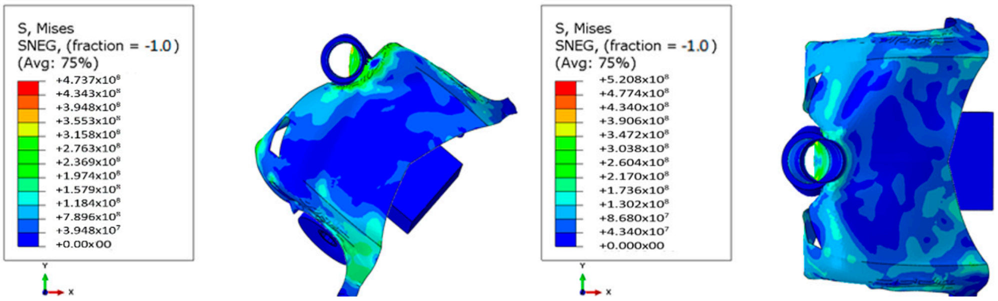
This could slow down the calculation, as well as introduce instabilities to the analysis. Moreover, since the study is performed on vehicles at high speeds, friction can be ignored. Furthermore, the material model of the discarded tire is assumed to be only hyperelastic with a stable Poisson's Ratio of 0.45. Additionally, no additional parameters, such as viscoelasticity, hyper plasticity and viscous plasticity, are considered. Damage parameters, such as the crushable foam mechanics, are also not considered in this study. The main reason for this is that material parameters of TDM 500 were not available when referring to its properties tested by Montella et al. [17].

4. Results

4.1. Parameterisation of TDM Thickness on Impact Energy Absorption on Street Pole and Vehicle

The first analysis that this paper demonstrates is the effect of the TDM-based thickness on street poles and the impact energy to ensure that the impact energy is mitigated due to the presence of the TDM-based reinforcement. Ideally, the impact energy should be reduced for both the vehicle and the street pole so that injury to the passengers can be reduced as much as possible and the risk of the street pole being damaged beyond repairs can be reduced as well. For these results, a common velocity of 17 ms^{-1} is used to make a qualitative analysis of this parameterization for both frontal and corner types of collisions.

When assessing the deformation of the reinforced steel street pole in comparison to the unprotected street pole conducted by Alardhi et al. [1], a small street pole deformation reduction of 2.0–4.0% is achieved when using TDM thicknesses of 15–35 mm, respectively. This finding can be seen in Figure 4. However, increasing the TDM thickness further does not reduce street pole deformations, suggesting that 35 mm thickness is optim



(**a**) (**b**)

Figure 4. Top view of the Mises stresses of the collision with (**a**) corner collision and (**b**) frontal collision.

This finding can also be validated by viewing Figure 5, where the corner impact shown is also the same for both 35 mm thickness and 45 mm thicknesses.

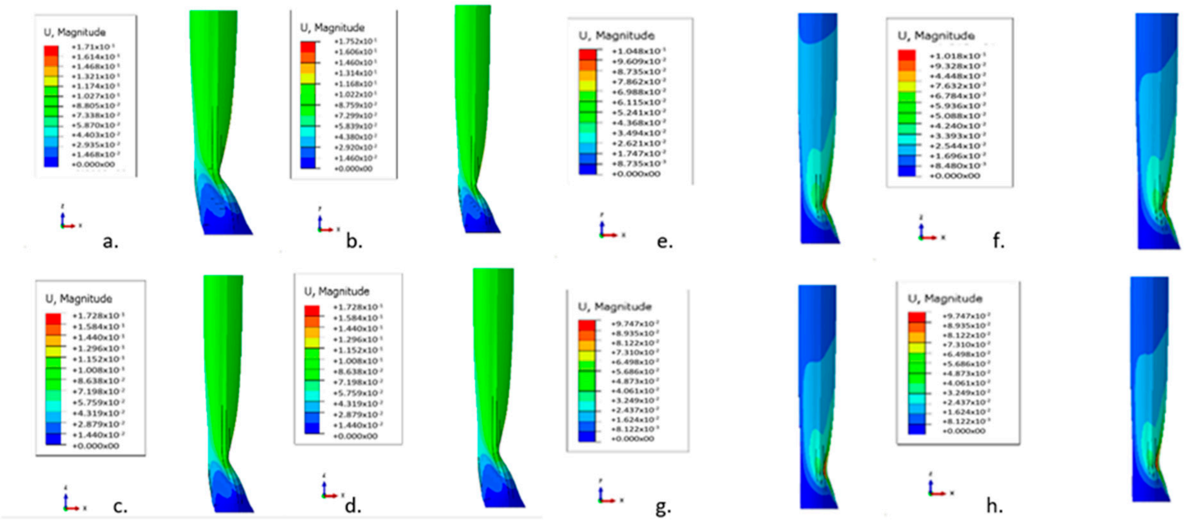


Figure 5. Street pole deformation with TDM reinforcement. (**a**–**d**) are deformation after a frontal collision on a street pole with thicknesses of 15, 25, 35 and 45 mm, respectively, while (**e**–**h**) are deformation after a corner collision on a street pole with thicknesses of 15, 25, 35 and 45 mm, respectively.

Compared to the frontal impact, the corner impact shows that with a thickness of 15 mm, the reduction of deformation is about 2%, and at 35 mm of reinforcement, the reduction of deformation is increased to about 9%, suggesting that the TDM reinforcement acts very well against corner collisions in comparison to the frontal collisions. Since many accidents are of this nature [3], it is beneficial that TDM reinforcement mitigates the risk of causing more injury and reducing the damage to the street pole. The reason why the results of reinforcements with thicknesses of 35 mm and 45 mm are identical could occur due to the material having a declared Poisson's Ratio of 0.45, which represents incompressibility. This results in the shielding exhibiting a rigid body rather than an energy absorber, which defeats the purpose of the need for TDM shielding.

The next properties analyzed are the energy absorbed by both the vehicle and the street pole during the simulation step time, which can be seen in Figures 6 and 7. The results are compared to those initially conducted by Alardhi et al. [1] on a clean collision between the vehicle and a standalone steel street pole using both frontal and corner impact simulations.

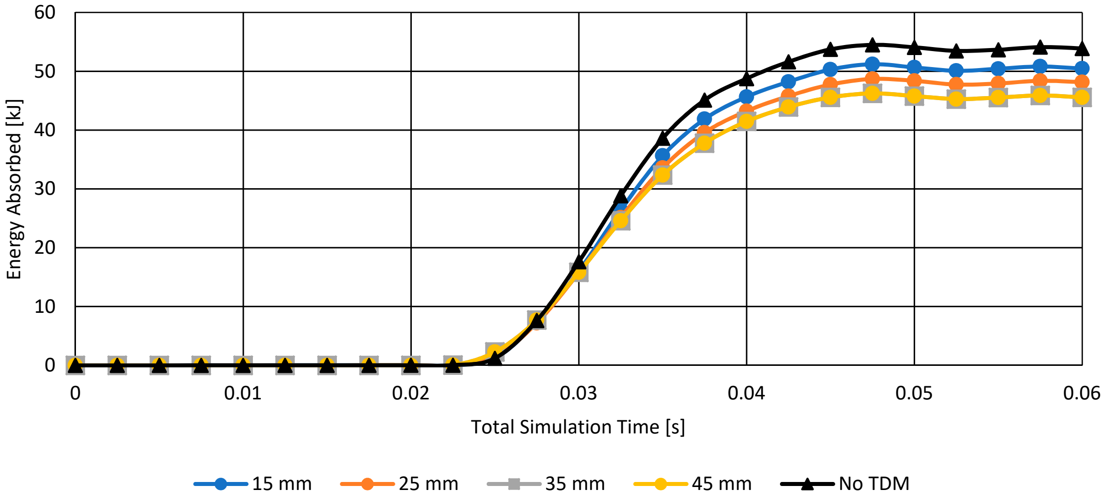


Figure 6. FEA results from energy absorptions of the street pole after being collided by a vehicle (frontal collision) using five different thicknesses of TDM shielding.

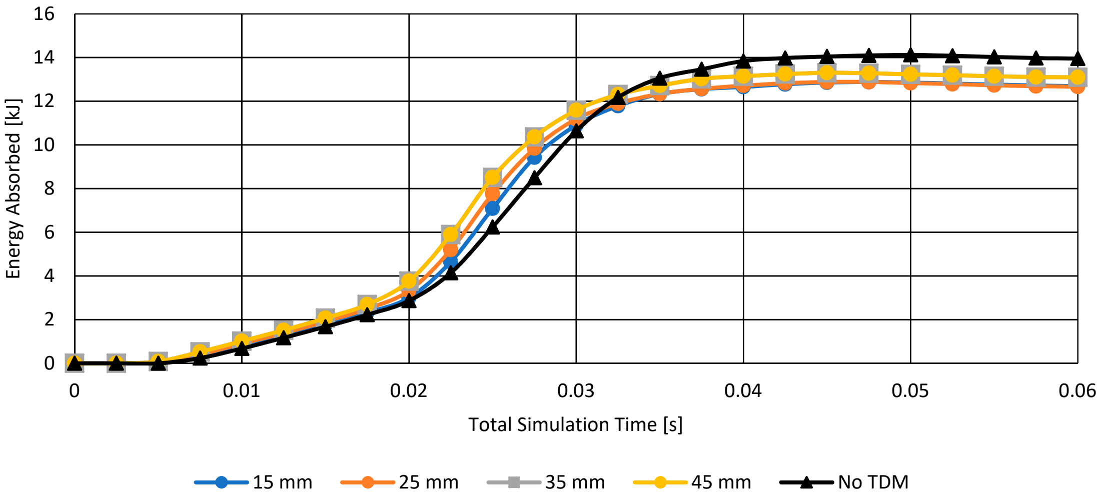


Figure 7. FEA results of energy absorptions of a vehicle after colliding on a street pole (frontal collision scenario) using five different thicknesses of TDM shielding.

From viewing Figure 6, the initial reduction of impact energy on the street pole when the vehicle has collided via the frontal impact averages between 4.5 and 5.2%. This reduction increases to between 13 and 15% when the thickness of the TDM increases to about 35 mm. These readings are significant in terms of street pole structural protection as this would decrease the chances of street poles losing their structural integrity and collapsing onto the vehicle. Furthermore, this effect also reduces the risk of the street poles suffering further damage. When analyzing the impact energy mitigations on the vehicle, however, while the overall impact energy of the vehicle is decreased by 5%, the car suffers by absorbing more impact energy at thicknesses above 35 mm compared to when the car collides with the street pole with reinforcements having a thickness below 35 mm. Therefore, it is imperative that optimization of these thicknesses is done to ensure that the passengers are mitigated by these absorptions as much as possible. Furthermore, after additional observations and comparisons between the impact energy absorbed by the street pole and the vehicle (especially between 0.2 and 0.4 s) as in the previous study [1] and the current one, it is shown in Figure 8 that the impact energy of the street pole is reduced throughout the simulation time. This might suggest that the vehicle is initially absorbing more energy when impacting a TDM-shielded pole. However, in fact, this only occurs because the distance between the vehicle is maintained for both simulations (in comparison to the work in [1]), so the contact between the reinforcement and vehicle happens first, and the energy absorption happens sooner than with the original unreinforced collision scenario. When analyzing the impact energies of the corner collision scenario, as seen in Figure 8, it can be observed that the reduction of the impact energy on the street pole is significantly lesser, with a thickness of 35 mm, than with the frontal collision scenario. While the frontal collision showed a mitigation of 5% on impact energy absorbed by the street pole when TDM reinforcement was applied, the impact energy by the corner collision was mitigated to about 30%. Since the corner collision scenarios are usually the more common forms of accidents between a car and a street pole, it can be suggested that TDM-based reinforcement can greatly decrease the damage caused on the street pole when corner collisions occur, and this was reflected by the significant reduction in deformation to the street pole.

Furthermore, these significant mitigation of impact energies were also evident on the vehicle, with Figure 9 showing that the vehicle's impact energies were significantly reduced due to the presence of the TDM material. The reduction varies between 28% and 43% depending on the thickness of the TDM reinforcement, suggesting that corner collisions on street poles shielded with recycled shielded tires can greatly reduce the risk of harm and injury to a passenger.

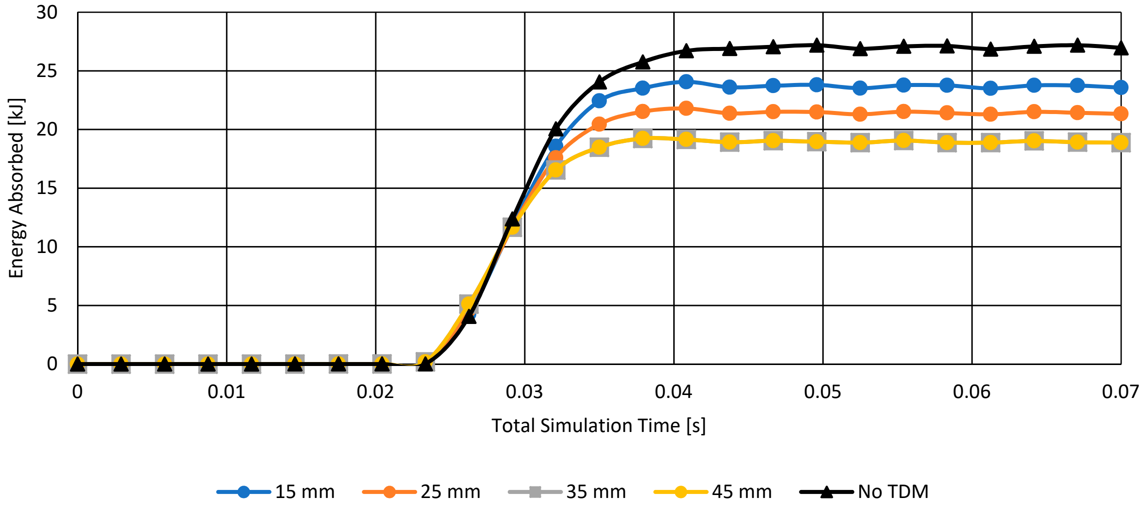


Figure 8. FEA results of energy absorptions of the street pole after being collided by a vehicle (corner collision scenario) using five different thicknesses of TDM shielding.

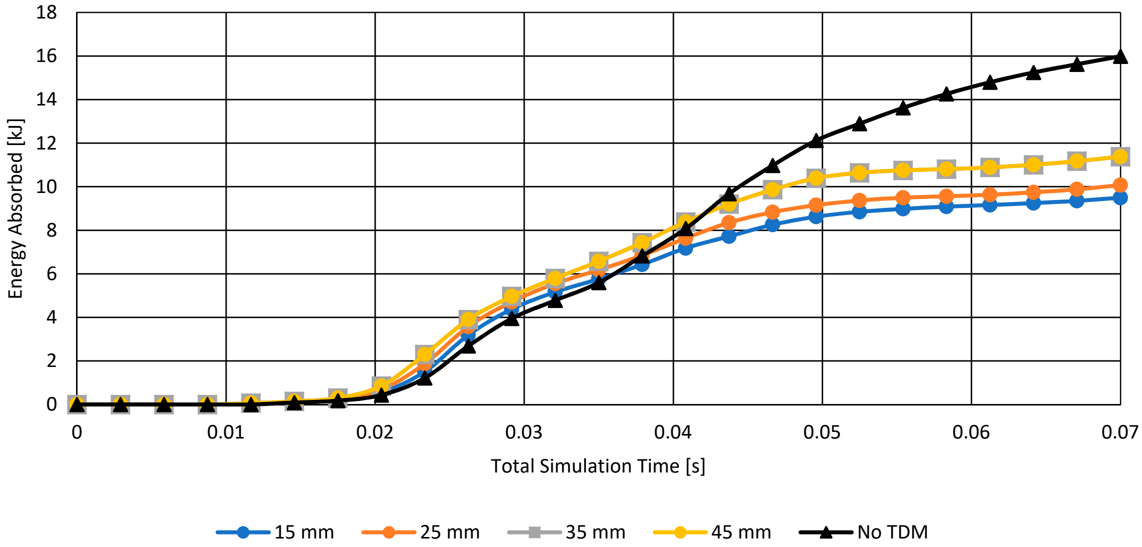


Figure 9. FEA results of energy absorptions of the vehicle after colliding on a street pole (corner collision scenario) using five different thicknesses of TDM shielding.

However, when comparing Figures 8 and 9, a peculiar observation was found that calls for further study on the optimization of these TDM-based reinforcements. When the thickness of the reinforcements was increased, the impact energy of the vehicle was seen to be higher than when the vehicle collided with the street pole using a lesser thickness. Therefore, while it is important that reinforcement using recycled tires need to be added to the pole, it should be noted that the thickness should be optimized, or passengers actually may suffer an increased risk of injury.

4.2. Variation of Vehicle Velocity on the Impact Energy Absorption on Street Pole and Vehicle

From previous results, it can be said that an analysis of the effect of TDM thickness on the vehicle and the street pole is established; it can be considered using a common thickness of 35 mm for the TDM-based shielded street pole to vary the velocity of the vehicle and understand its impact on the mitigation of the impact energy on both the vehicle and the street pole. When initially assessing Figure 10, it can be observed for all velocities, TDM-based reinforcements ensure mitigations on the impact energy that the street pole will receive due to a collision.

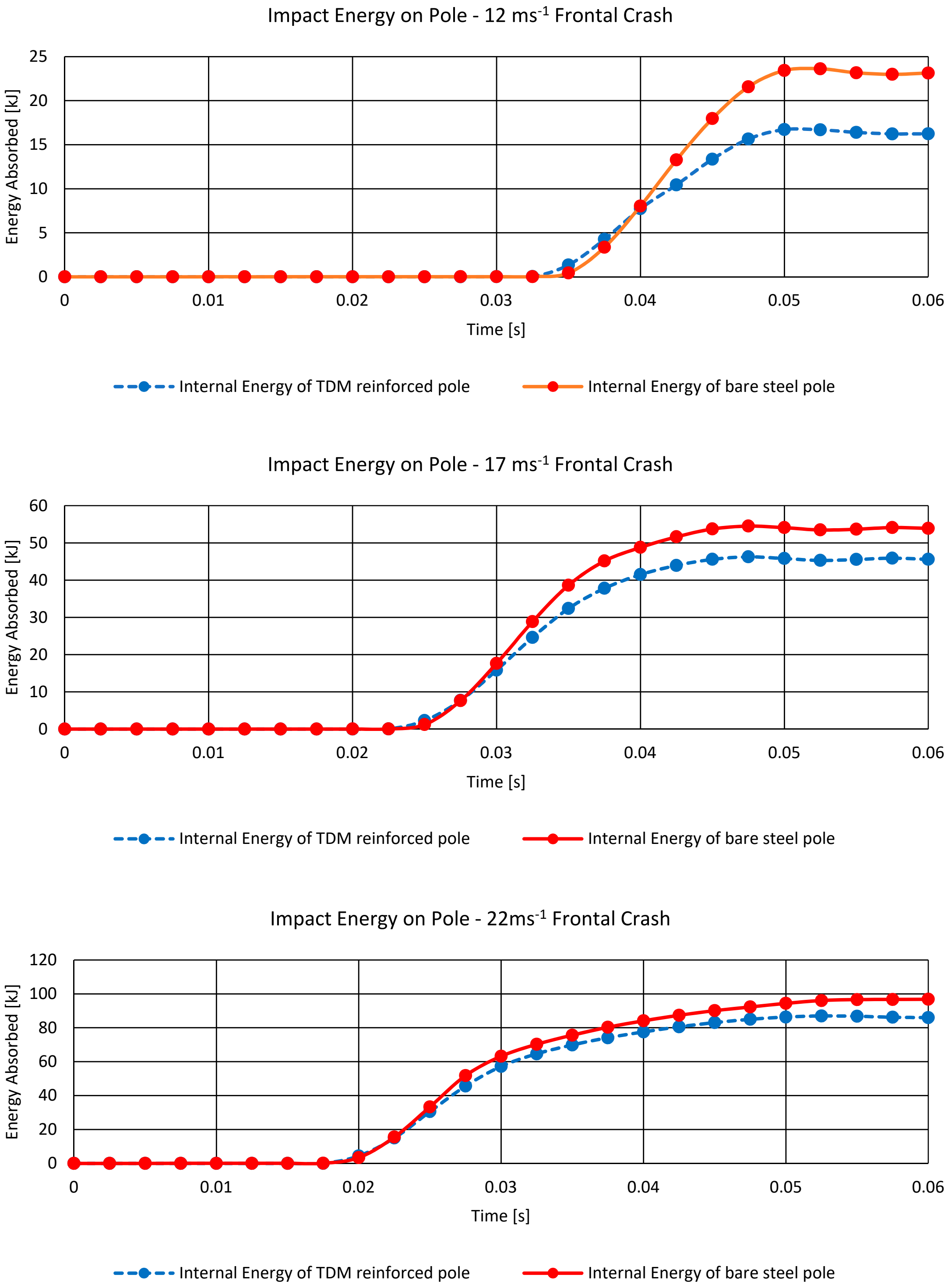
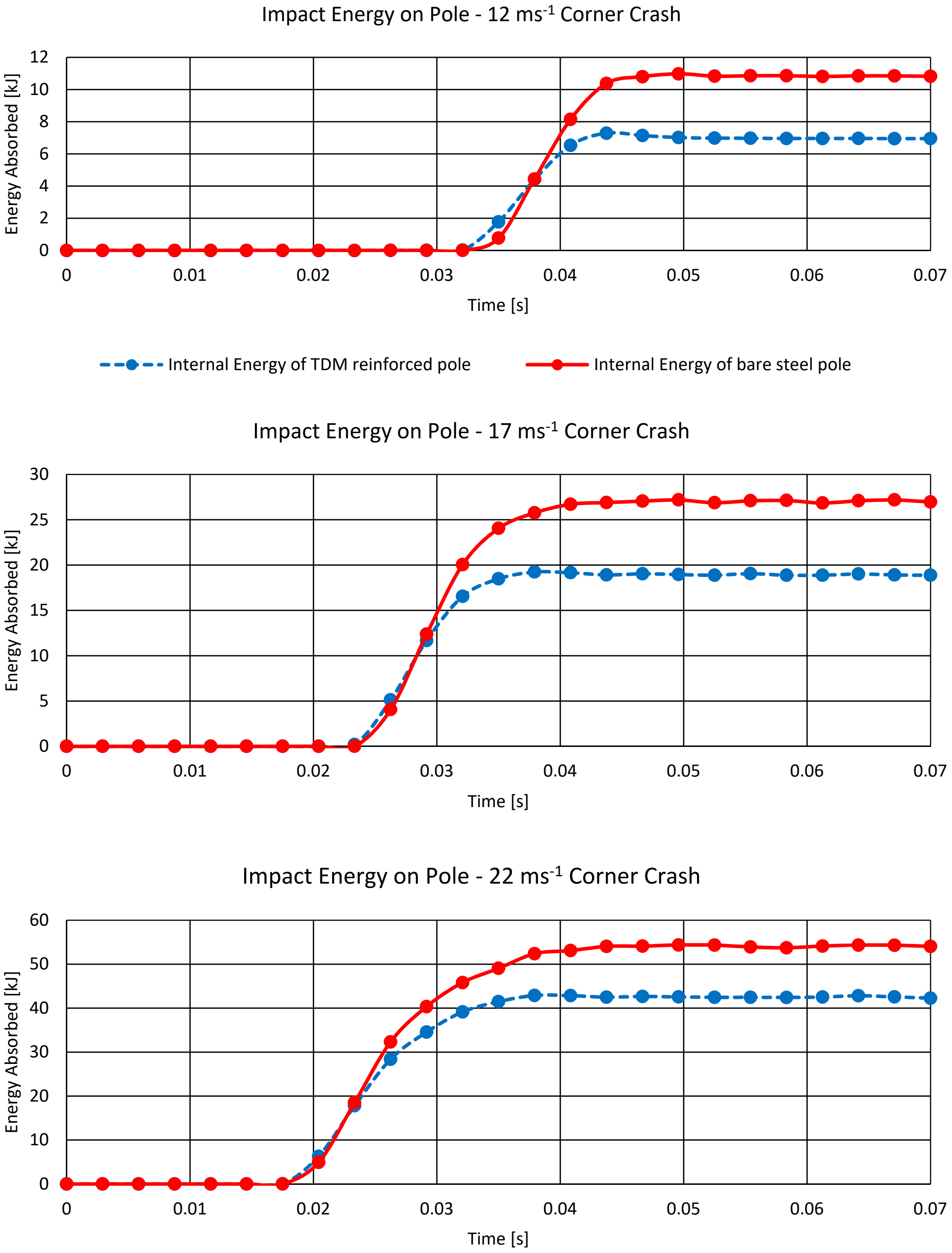


Figure 10. Impact energies were absorbed by the street pole (one as a bare street pole and the other shielded by TDM material of 35 mm) when collided by the vehicle through a frontal collision scenario at speeds of 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}.

However, the magnitude of these mitigations decreases with increased velocities. For instance, the street pole's impact energy is mitigated by 22.5% at speeds of about 12 ms^{-1}. However, when the velocities are increased to about 17 ms^{-1} and 22 ms^{-1}, the influence of the mitigation diminishes with a decrease in energy to about 5.2% and 1.15%, respectively. Therefore, at the highest velocity, since the mitigations are low, TDM reinforcement risks of still cause no difference to the damage suffered on the street pole. With that being stated, it is evident that the TDM-shielded street poles are essential in reducing the overall energy absorption of the street pole during a collision. On the further assessment of the impact energy absorption of street poles during corner-based collision scenarios, as seen in Figure 11, the mitigations shown complement the previous statement, with results showing a reduction of impact energies between 22 and 28% for velocities at 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}. Contrastingly though, the energies reduced are much higher compared to the frontal collision. Since the corner collision scenarios are more likely to occur in a practical scenario, the benefits of having the TDM reinforcement emphasize its necessity to protect the street pole from further damage.


Impact Energy on Pole - 12 ms^{-1} Corner Crash

Impact Energy on Pole - 17 ms^{-1} Corner Crash

Impact Energy on Pole - 22 ms^{-1} Corner Crash

Figure 11. Impact energies were absorbed by the street pole (one as a bare street pole and the other shielded by TDM material of 35 mm) when collided by the vehicle through a corner collision scenario at speeds of 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}.

While it was expected that the nature of the results of the frontal collision would be similar when comparing the energies absorbed by the street pole to the energies absorbed by the vehicle at respective speeds, this did not happen. As shown in Figure 12, at low speeds, TDM-shielded street poles exert more energy onto the vehicle, although this increase in energy is not too sufficient to create significant damage to the vehicles. For example, at speeds of 12 ms^{-1}, the energy exerted is 7.2% higher on the vehicle by the TDM-shielded street pole.

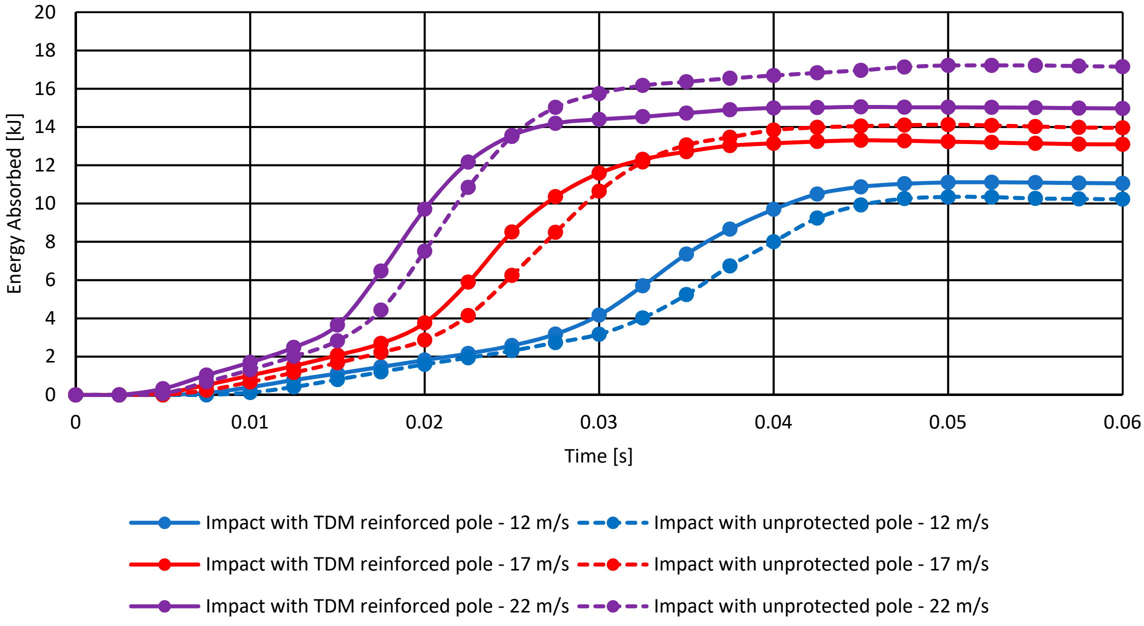


Figure 12. Impact energies absorbed by the vehicle on a street pole (using the frontal collision method) with a TDM reinforcement of 35 mm using three different speeds at 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}.

When comparing this result to the results of the energies absorbed by the street pole, the total energies, in this case, have been mitigated by a large margin. However, when the velocities are increased, as shown in Figure 12, the results then show that TDM-based shielded street poles mitigate the energies absorbed by the vehicle. For instance, the energies of the vehicle are reduced by 7% and 14% at speeds of 17 ms^{-1} and 22 ms^{-1}, respectively, which greatly increases the chances of passengers in the vehicles avoiding serious injuries. Moreover, from comparing the results of the impact energy absorbed by the vehicle and street pole, it can be seen an inverse relationship to the amount of mitigation that the two parts encounter: that is, as velocity increases, the mitigation decreases for the street pole, but there seems to be a significant increase in mitigation of energy onto the vehicle suggesting that the TDM-reinforcement is in fact greatly reducing factors that include risks of the street pole from undergoing severe damages at low speeds while reducing the risks of injury or possible death for passengers when the vehicle impacts the street pole at significantly higher speeds.

After the investigation of the impact energy of the street pole and vehicle during a frontal collision, the corner collision was then investigated as a reliability check. As expected, at low speeds, the TDM-based protection provides minimal mitigation for the vehicle, although, in this case, the energy exerted by the shielded street pole is now lesser on the vehicle in comparison to the frontal collision. However, when the velocities are increased, it can then be seen that the mitigation of impact energy onto the vehicles becomes quite significant, as shown in Figure 13.

For instance, at 12 ms^{-1}, the mitigation of the impact energy onto the vehicle is only 6.25% but at higher magnitudes of velocities, the mitigation increases to 28% and 25.8% of the impact energies at velocities of about 17 ms^{-1} and 22 ms^{-1}, respectively. Since corner collisions are usually the most common collision in practical accidents, such results emphasize the importance of the need to use TDM reinforcement on streetlights to protect the road authority's investment on the street poles as much as possible while also increasing the chances of passengers from avoiding major injuries. Lastly, the results will also demonstrate some of the deformation contours that are visualized after simulating both the frontal and corner collision on a TDM-shielded street pole. It is evident that at low speeds, a frontal crash exerts low deformations at only some regions of the geometry on the street pole. Therefore the energy is not fully absorbed by the vehicle, which explains why the mitigations are less in such scenarios. However, at higher speeds, the deformations are quite significant throughout much of the geometry, especially the clear compressive degradation caused by high compressive forces at vehicle velocities of 17 ms^{-1} and 22 ms^{-1}.

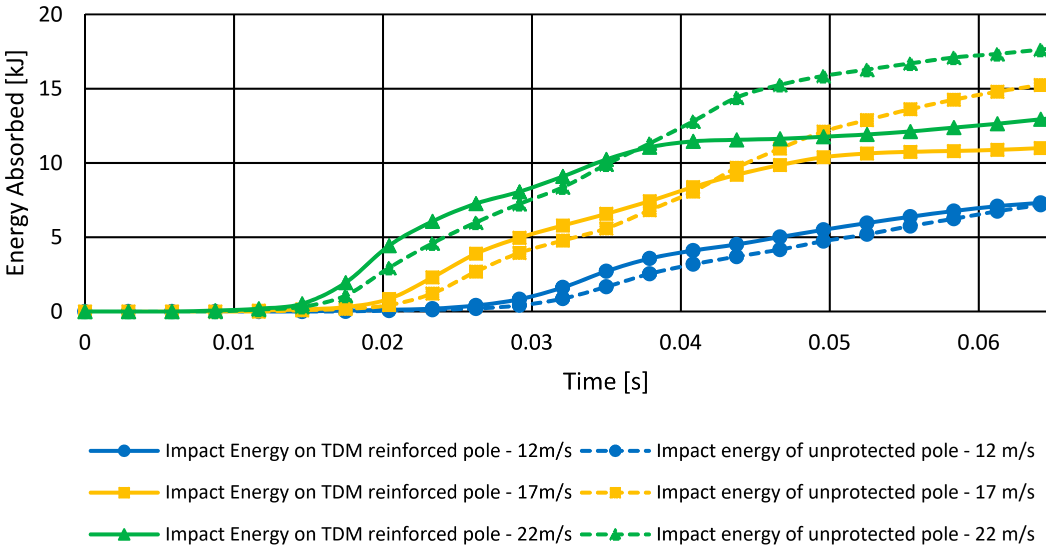


Figure 13. Impact energies absorbed by the vehicle on a street pole (using the corner collision method) with a TDM reinforcement of 35 mm using three different speeds at 12 ms^{-1}, 17 ms^{-1} and 22 ms^{-1}.

5. Conclusions

This research articulately stresses the need to utilize discarded tires in TDM so that they can be used as a protective shield around the street pole. With impact energy mitigations between 22% and 28% for low-speed applications and mitigations of between 4% and 7% at higher speeds, transportation authorities can accomplish objectives of reducing the chances of failure on the structural integrity of the street pole (especially at low speeds). These results also find sources to reduce the chances of passengers suffering from serious, life-threatening injuries. From this investigation, it is also confirmed that the speed of the vehicle has a relationship with the outcome of the collision. For low vehicle velocities, the TDM shielding significantly mitigates kinetic energy transferred onto the pole. This would significantly help in the possible decrease of costs to repair street pole structures. However, at such speeds, the impact it mitigates on the vehicle is reduced. However, this may not be very problematic as low-vehicle collisions have low risks of injuring the user. At higher velocities, the scenario shows that TDM shielding significantly reduces the transfer of energy to the vehicle. This is vital as the risk of injury to passengers is greater at high-speed collisions. This is especially true when viewing results of corner collision simulations with mitigations peaking at 28%. Therefore, the increase in mitigation of energies to the vehicle is vital to protect the user. The mitigations of energy to the pole are somewhat similar in all scenarios showing that the magnitude of mitigation of energy onto the pole may be similar at different speeds. More variations of speed, however, may be required to confirm this finding. The report shows that there is an asymptotic trend after testing TDM thicknesses of over 35 mm, as seen in Figures 6–9. One suggested improvement is to increase the range of thicknesses to account for results at a thickness of 55 mm. This can further improve the reliability of the results. Furthermore, since the stresses on the TDM-based shield experienced stresses to more than 20 MPa (which is way beyond the plastic limit), the investigation of plasticity, hardening and these influences on the mitigation of impact energies on the street pole and vehicle should be further studied.

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