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Assessment and Design Enhancement of the Front End Energy Absorption Mechanism of a Locomotive Based on an Impact Scenario

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A B S T R A C T

This research is concerned with weighing the behavior of the front end energy absorption system of a locally manufactured locomotive in crash situations. The causes of the extensive damages to the energy absorption apparatus that includes the crash element and the buffer are studied. By choosing the proper damage model the conditions of the accident is simulated by using the ABAQUS engineering software. The amount of the absorbed energy during a crash is estimated. Improvement of the existing mechanism is also considered. A metal honeycomb energy absorber is proposed to increase the energy absorption capacity of the locomotive front end.

1. Introduction

A passenger train on duty equipped with a locally manufactured locomotive overran the red signal at a speed of $107\frac{\mathrm{km}}{\mathrm{hr}}$ and entered a station at the reduced speed of $61\frac{\mathrm{km}}{\mathrm{hr}}$. It ran into a freight train that was already stopped at this station. This accident, sadly, caused fatalities and serious injuries amongst the passengers. Also, four railway employees were injured and sent off to hospital. The locomotives and some railway vehicles from both trains were extremely damaged [1]. Pictures from the scene of the accident are provided in Figures 1&2.

A similar accident occurred on the 15th of November 1992 in Northeim Germany. In that case the high-speed train D482, due to the faulty braking system and at a speed of $100\frac{\mathrm{km}}{\mathrm{hr}}$ ran into a freight wagon. Klinger and Bohraus [2] in 2014, had investigated the causes of destruction of all components of the locomotive in this accident. In July 2008, a high-speed train ICE3 at a speed of $330\frac{\mathrm{km}}{\mathrm{hr}}$ derailed. Klinger and Bettge [3] in 2013 reported that the fracture that emerged from the locomotive axle fatigue was the cause of this accident. Zhang et al. [4] in 2006 investigated the reason of structural failures of various high-speed trains in China. After studying the processes of design, repair and maintenance of these locomotives, they provided some suggestions to optimize the design of different components of the locomotives.

This research is concerned with the crash energy absorption components of a locally manufactured (IrSa) locomotive. A case is made based on the information from a real case accident involving this type of locomotive. The features of the existing energy absorbing components in this locomotive are described. The behaviour of these components and their degree of involvement and possible damages during a collision scenario is investigated. The role of other components in the locomotive chassis and its head-chassis in a crash scenario is evaluated. Application of honeycomb energy absorption structure and its design for improving

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the crash energy absorption of the locomotive is examined.

Figure 1. The scene of the accident involving passenger and freight trains [1]

Figure 2. Relief and rescue operations after the accident [1]

2. Reviewing the Functionality of the Front End Energy Absorption System in the Damaged Locomotive

In IrSa locomotive, the energy of the collision is absorbed by components that are embedded in the front end of the locomotive. These components include a buffer and a crash element. The buffer into which a spring is embedded, absorbs the primary effects of the collision such that the vehicle possibly does not end up with irreparable damages. If the primary collision force is too large, the crash element behind the buffer, by using a folding mechanism, deforms and absorbs the energy of the collision. The components of the front end energy absorption mechanism in IrSa locomotive are presented in Figure 3 [1].

From observations after the collision it is known that in this case the buffer and the crash element were completely destroyed. From Figure 4, it is clear that the collision force almost horizontally applied on the crash element and also this force was transferred to the other parts in this compartment. Another important point to notice is that is that the crash element in addition to folding can also rupture. This is due to the thickness of its metal sheet. This metal sheet tends to rupture during the collision. Also, the shear stresses during the collision causes the rupture of the structure from its corners which is formed from the micro void coalescence. Eventually, this rupture can spread into other parts in the energy absorber mechanism.

Observations from the scene of the crash that is partly depicted in Figure 4, made it clear that the force exerted on the buffer and crash element was more than its yielding strength. Consequently, both elements endured plastic deformation. The plastic deformation actually facilitates absorption of the collision energy. Remarks after the accident also prove that the energy absorption mechanism did not dampen all collision energy and the excess energy also transferred to the other sections of the locomotive frontal parts. It is presented in Figure 5 [1] that in addition to the destruction of the crash element and buffer the locomotive head-chassis was also damaged. The other sections of the locomotive were not seriously damaged.

Figure 3. Front end energy absorbing equipment in IrSa locomotive [1]

The subject has caused the initiation of an analytical assessment of the functionality of the locomotive collision energy absorption mechanism. In what follows the modelling of the buffer and the crash element inside the locomotive frontal end is elaborated. The modelling is based on the ABAQUS engineering software. Through the simulations, the sizes of the collision energy absorptions are estimated.

3. Modelling the Energy Absorption Mechanism

Modelling of the energy absorption system of IrSa locomotive is accomplished by using the ABAQUS engineering software platform. The dimensions of the buffer and the crash element are according to the data that are provided in Figures 6&7 [1]. The crash element is a tapered thick wall tube and the buffer is a circular tube that is screwed to the crash element by using a square plate. The Buffer is made of a double tube structure so that its internal tube can move inside its outer tube. There is a spring between these two tubes in order to absorb the primary collision energy. The modelling of the buffer and the crash element is presented in Figure 8.

In order to simulate the conditions of the collision, the end of the crash element is attached to a rigid foundation. The simulation includes a rigid metal sheet as an impacting object with the centralized mass of 85 tons that is equivalent to the mass of the locomotive. The simulation mimics the impact of this huge mass to the buffer at a simulated speed of 61km/hr. The surface to surface algorithm from the ABAQUS software is used to collide the two bodies. Also, the general contact algorithm from ABAQUS is used to connect and contact the various parts of the energy absorption system with each other during the collision. In both cases the friction coefficient is set to 0.3 that is equal to the friction coefficient for steel to steel contacts.

According to the available data, the buffer and the crash element material is steel S355J2G3. The simple tension tests to obtain the properties of this steel are reported in ASTM E8M-09 [5].

According to this standard test, the Young's modulus for this steel is 200Gpa, the Poisson's ratio is 0.3 and the density is 7800 kg/m^3. Also according to the fact that the collision happens in a very short period of time and the deformation rate is very high, the properties of the material must be accounting for the different strain rates. For this purpose, the stress-strain diagram of steel S355J2G3 at different strain rates, according to reference [6] is considered. In order to mesh the elements of the modelling, the facility C3D8R that is provided in ABAQUS software is used. The mesh sensitivity analysis was carried out to ensure that the results are independent from the number of the elements. A total number of 56614 elements were used to generate the meshes for the modelling. A schematic of the frontal collision energy absorption mechanism of IrSa locomotive in ABAQUS software is presented in Figure 9. If the collision is strong enough the crash element sheet ruptures. The folding and rupture of this sheet is to handle the energy absorption during

(a) **(b)**

Figure 4. (a) Destruction of the crash element and buffer (b) rupture of crash element sheets from the corners due to the shear stress concentration [1]

Figure 5. The damage to the front parts of the locomotive, including a buffer, the crash element and head-chassis [1]

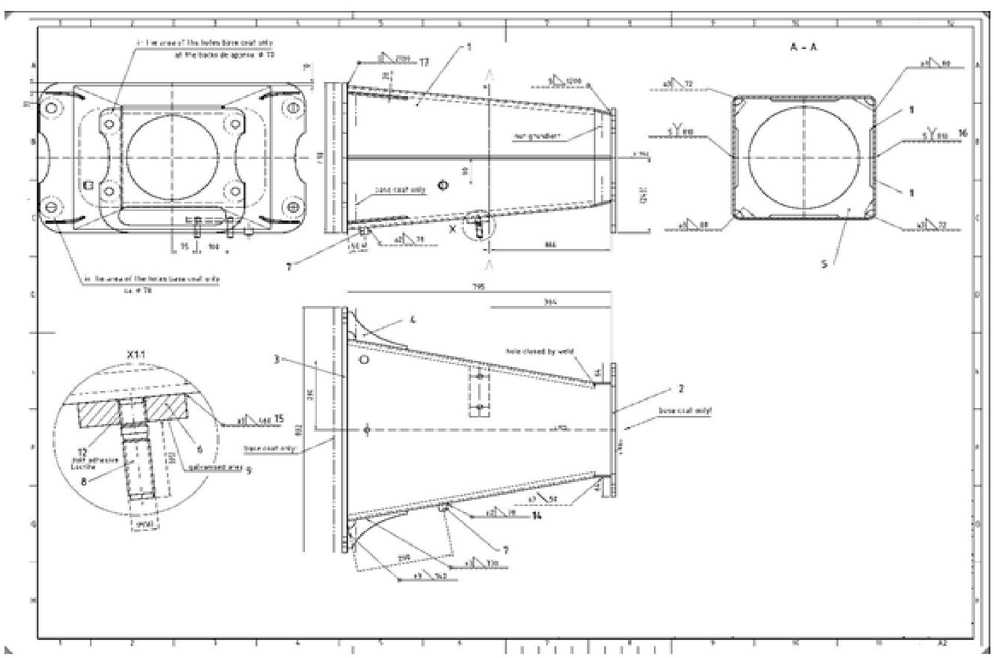

Figure 6. The crash element [1]

the collision. Therefore, for the accurate estimation of the absorbed energy both energy absorption mechanisms need to be accounted for.

3.1. Calculation of the Energy Absorption during the Collision

For the modelling of rupture during the collision a damage model need to be suggested. Generally, the damage models may be divided

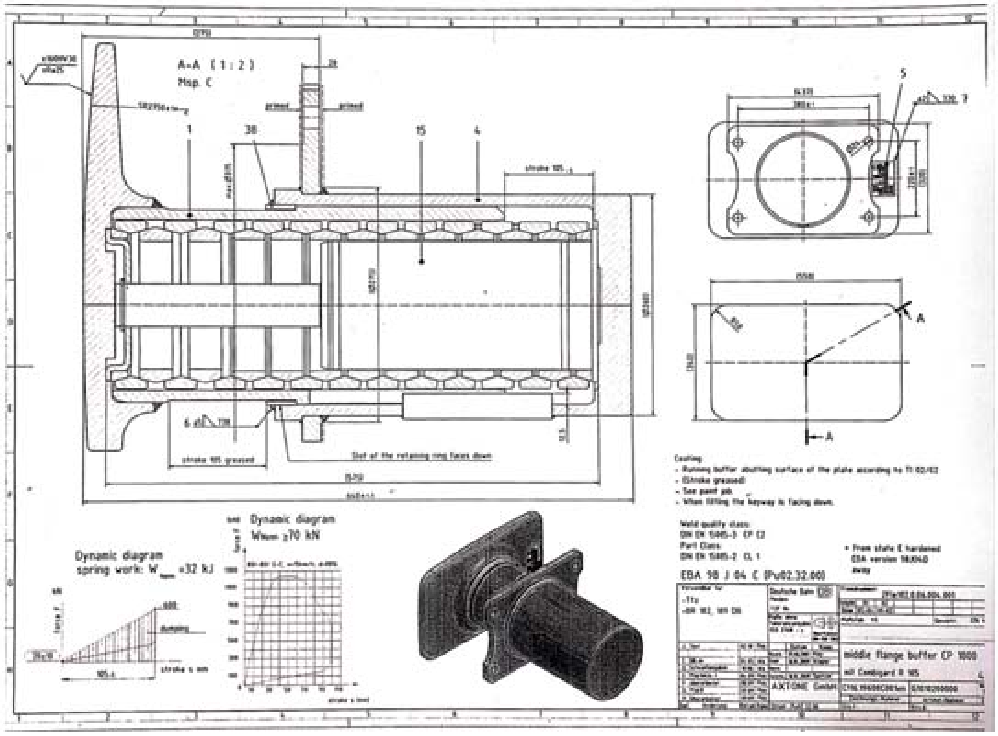

Figure 7. The buffer [1]

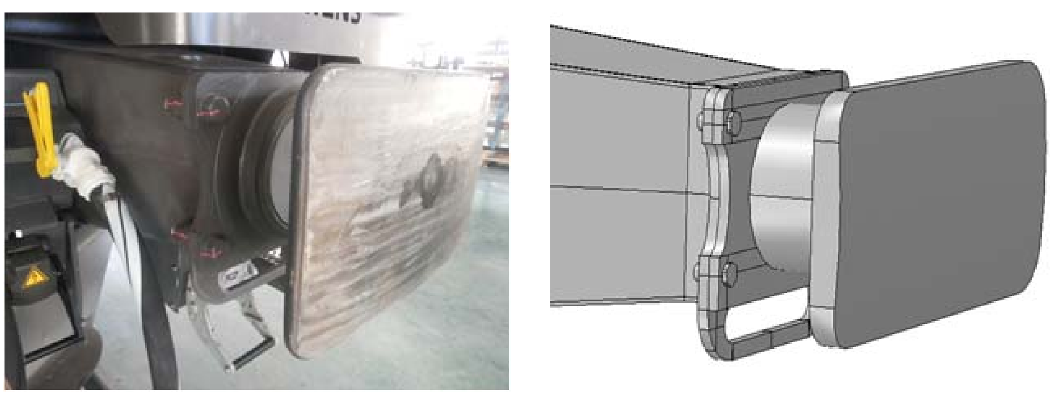

Figure 8. The model for the energy absorption system of IrSa locomotive in ABAQUS

into two general categories. These include the continuous damage models that are available in ABAQUS software and the microstructural damage models. The use of the continuous damage models in the finite element software is simple. However, calculation of the damage parameters in these models needs plentiful of experimental data. The microstructural damage models describe the influence of the tri-axial stresses on the damage behaviour, and the parameters are independent of the geometry of the segment.

In order to model the destruction in the crash element of IrSa locomotive data from the research by Hosseini Tehrani and Ferestade [7] is selected. In that research, the energy absorption in a tapered thick wall tube was studied. An analytical solution for the estimation of the variations of the force during the collision was presented.

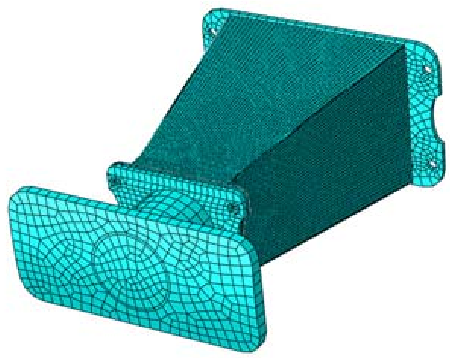

Figure 9. The model for the energy absorption mechanism of IrSa locomotive in ABAQUS software

Different damage models by using numerical solutions were examined. It was concluded that the modified Rousselier damage model is the most suitable for estimating the energy absorption in thick-wall energy absorbers. The results were experimentally validated, Figure 10.

3.1.1. The Modified Rousselier Damage Model

This model is a microstructural damage model. In this model unlike the continuous damage models the substance is assumed to be a set of heterogeneous cells. The strain accumulation process that leads to the soft fracture in this damage model is complicated. Metallurgical observations demonstrate that the fracture of soft metals, often starts with nucleation, growth and integration of micro voids under tensile stresses. Therefore, in these damage models, the materials are considered as porous structures.

The modified Rousselier damage model, for the first time, was proposed by Hutchinson and Nahshon [8]. This model assumes that both types of fracture are caused by tensile and shear stresses. The isotropic hardening model is used for this type of the damage model. It uses two intrinsic variables for the inclusion of the material damage processes. These include the plastic strain p and the rate of cavity expansion f that is also called the damage variable. The Rousselier damage model also includes the yield potential, stress-strain relation and the variations of the damage variable.

The yield potential function in Equation (1) links the damage growth rate with the hydrostatic tension:

$$\varphi = \frac{\sigma_{eq}}{\rho} - R(p) + Df\sigma_1 exp\left(\frac{\sigma_m}{\rho\sigma_1}\right) = 0 \quad (1)$$

In this equation $\sigma = \sigma_d + \sigma_m I$ is the Cauchy stress tensor, σ_d is the Deviatoric stress, σ_m is the hydrostatic stress, I is the second order unit tensor, σ_{eq} is the Von Misses equivalent stress, $\rho = (1-f)/(1-f_0)$ is the relative density, f is the damage variable or the cavity volume expansion, f_0 is the initial size of the cavity in the material, $R(p)$ is the material hardness function, p is the plastic strain equivalent and D and σ_1 are the material constants for Rousselier equation.

The damage variable for the modified Rousselier damage model is as follows:

$$f = \frac{(D+k_w\omega(\sigma))f_0}{(D+k_w\omega(\sigma)-Df_0)e^{-(D+k_w\omega(\sigma))p}+Df_0} \quad (2)$$

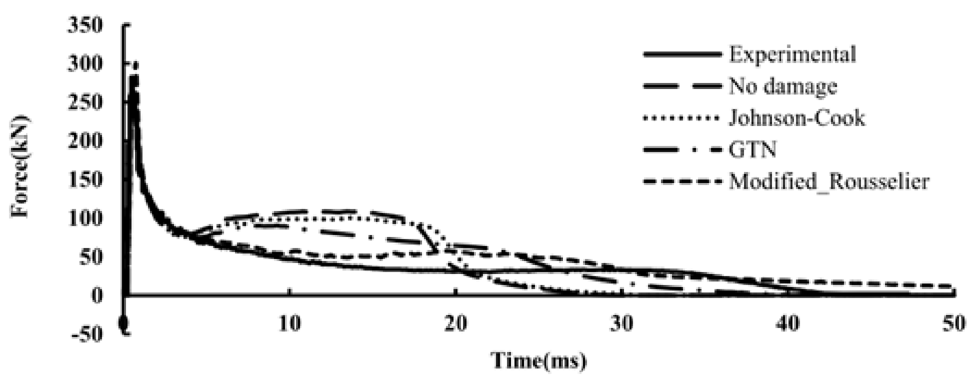

Figure 10. Force versus time for three different damage models and the experimental results [7]

where:

$$\omega = \left(\frac{27J_3}{2\sigma_{eq}^3}\right)^2 \quad (3)$$

The modified Rousselier damage model is not among the damage models in ABAQUS software. Therefore, in needs to be added to this software. To serve the purpose, the Vumat subroutine is used. The programming adjustments are based on the procedures that are reported in reference [9]. Also, the parameters D and σ are obtained from reference [10]. In reference [10], the damage model of Rousselier is used for the steel type A508 CI 3. The mechanical properties of this type of steel are reasonably compatible with the mechanical properties of the steel that is used in the structure of the crash element of IrSa locomotive (Table 1). Reference [10], uses $\sigma = 490\ Mpa$ and $D = 2$ for the numerical simulations.

Table 1. A comparison of the mechanical properties of A508 CI3 and S335J2G3

Steel	Young's modulus (GPa)	Yield strength (MPa)
A508 CI 3 [11]	205	380
S335J2G3 [5]	200	355

4. Simulation Results

The simulations are performed for a time duration of 0.03 sec. The corresponding results are presented in Figure 11. There is a decent agreement between the simulated and the real outcomes. Predictions for the spread of the damages due to the collision, and the metal ruptures in the crash element metal pieces are reasonable. The shear stresses during the collision, cause the rupture of the corners that then spreads along the width of the crash element. The crushing force of the collision causes the formation of the metal folding with the rupture in the crash element. From these set of results, it is concluded that the modified Rousselier damage model is reliable for the prediction of the metal damages during the collisions.

Figure 12 presents the total absorbed energy in terms of the crauhed displacement. The estimation for the total energy absorption during the collision is at 474472J. This size of energy is spent on rupturing the metal sheet, folding the crash element, overcoming the buffer resistance and pressing the spring in the energy absorption mechanism. The simulation results indicate that 504mm of the buffer length and the crash element were crushed during the collision to absorb the collision energy. Considering the facts from the accident, undesirably, the head-chassis and chassis of the locomotive were also damaged. Therefore, one may reach at the conclusion that under circumstances the design of the energy absorption system in this locomotive may not be up to the task. The performance of the energy absorption system in this locomotive in a real case scenario possibly will not be acceptable.

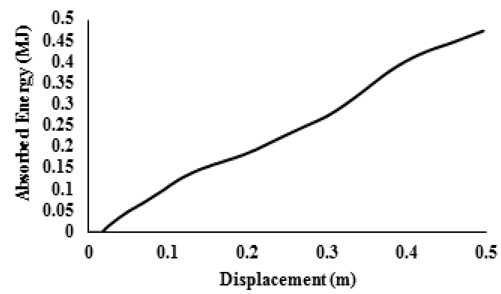

Figure 12. The absorbed energy versus crushed displacement

5. Improving the Energy Absorption Capacity to Reduce the Damages

There are a variety of methods in order to improve the energy absorption capacity in thin and thick wall crash elements. In some of these methods, specific materials are used to fill in the crash element. These may include metal foams [12, 13], metal honeycombs [14, 15] and composites [16]. The shape optimization [17], the triggering mechanism [18] and some other geometrical modifications [19] are also available methods for improving the energy absorption capacity. Amongst these, the methods that relate to the changes in the crash element geometry are more applicable for the reduction of crash initial force [20]. On the other hand, changing the geometry of the crash element, affects the design of the other features in the locomotive.

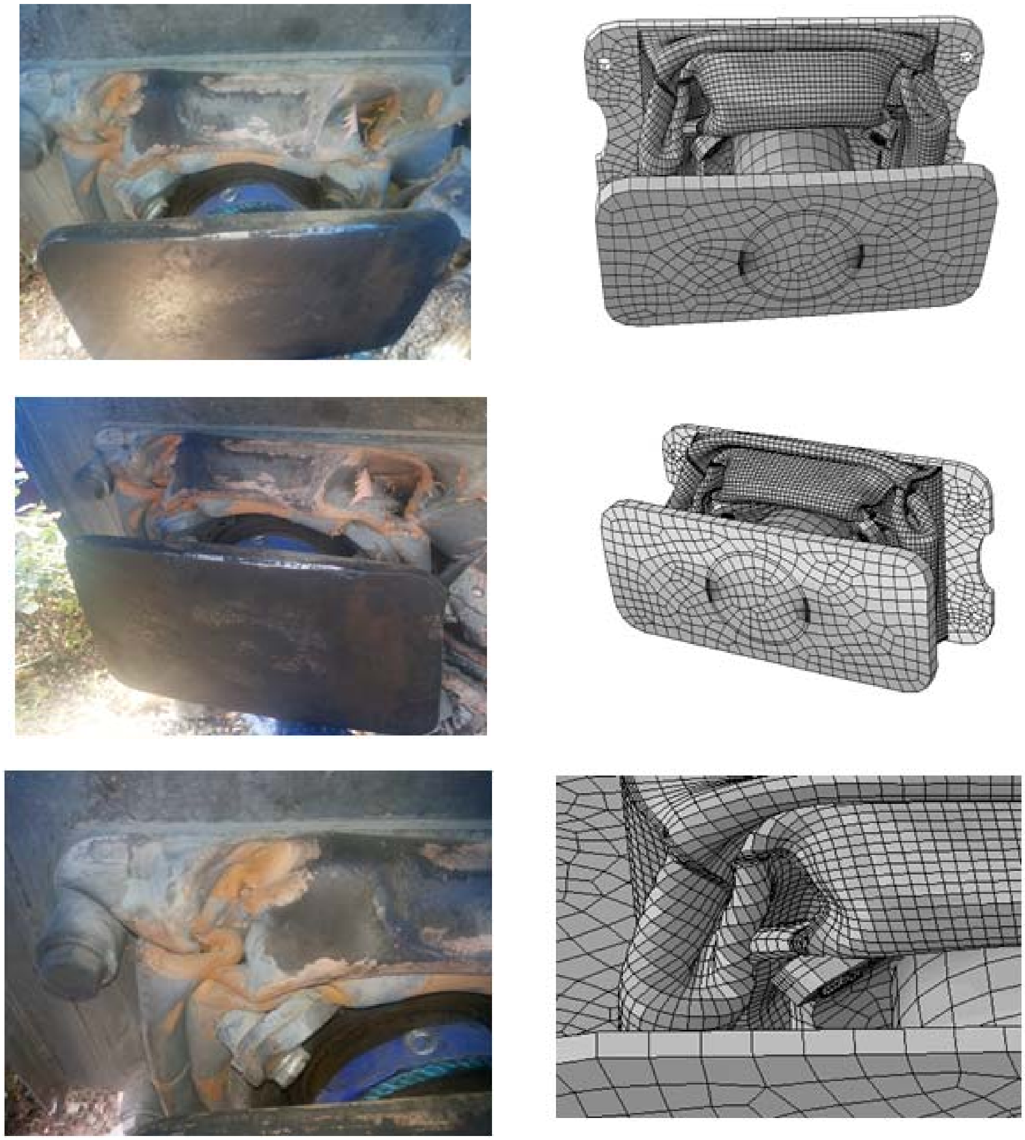

Figure 11. A comparison of the numerically simulated deformation and the real crash results

It is then decided to add a metal honeycomb structure inside the crash element to improve energy absorption during the collisions.

5.1. Design of the Honeycomb Structure

A hexagonal honeycomb structure is designed to increase the energy absorption. The side length of each hexagon is set at 47.5 mm. All hexagons are non-filled to reduce the mass of the structure. Due to the tapered geometry of the crash element some of the hexagons in the honeycomb structure are cut to properly occupy the empty spaces inside the crash element. Furthermore, the honeycomb structure is made of an aluminium alloy with $\rho = 2700\ {kg}/{m^3}$, $E = 70\ Gpa$, $\upsilon = 0.33$ and $\sigma_Y = 145\ Mpa$. The mass of the honeycomb structure is 16.67 kg that in comparison with the train mass is negligible. The modelling of the honeycomb structure is presented in Figure 13.

The ABAQUS modelling for this component has used 110863 meshes and is presented in Figure 14.

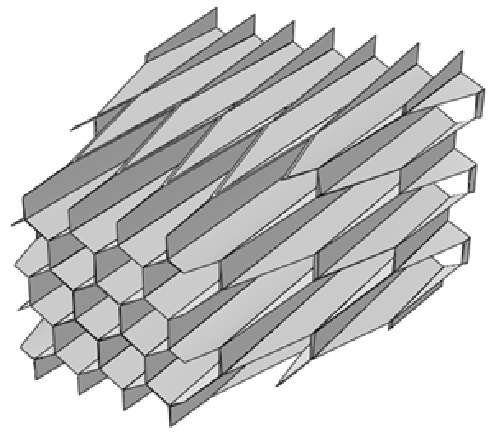

Figure 13. Modelling of the honeycomb structure by using the ABAQUS software

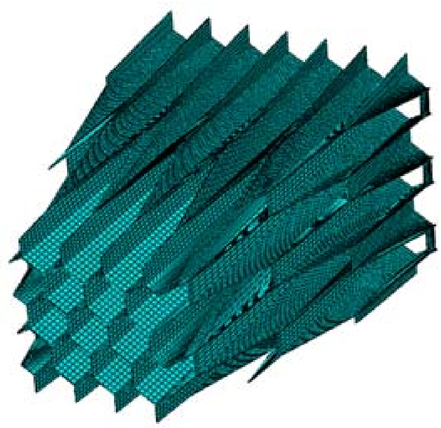

Figure 14. Honeycomb structure meshing in ABAQUS software

5.2. Simulation Results with the Inclusion of the Honeycomb Structure

Having inserted the honeycomb structure into the model for the crash element the original scenario for the collision was repeated. The results of the simulations are presented in Figures 15&16. For this case, the estimated amount of the absorbed energy is 828724 J. This is equivalent to 74.6% increase to the size of the collision energy absorption. From this set of the results it is also clear that at the presence of the honeycomb structure the rate of energy absorption by the crash element improves as the time elapses. This is due to the fairly smart design of the honeycomb structure that is presented in Figure 17. This honeycomb structure is designed in such a way that during the collision, as the time elapses, the front side of the structure collapses more. Consequently, as the time passes on the honeycomb structure behaves more like a solid body. This type of behaviour in the honeycomb structure saves the other components of the locomotive from the spread of the damages.

In Figure 16, the initial peak of the crash force decreases 37% with using the honeycomb structure. It is due to the honeycomb material ductility and its design geometry. However, the size of the force increases when the collision time elapses in comparison with the case when the honeycomb structure does not exist. This increase in the size of the forces endured by using the honeycomb may cause excessive acceleration and damages to the train passengers during the crash. Therefore, the Head Injury Criterion (HIC) needed to be calculated to make sure that the application of the honeycomb structure does not add to the likely injuries to the train passengers.

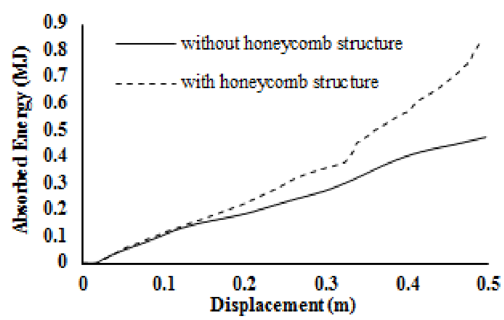

Figure 15. The absorbed energy versus crushed displacement with and without honeycomb structure

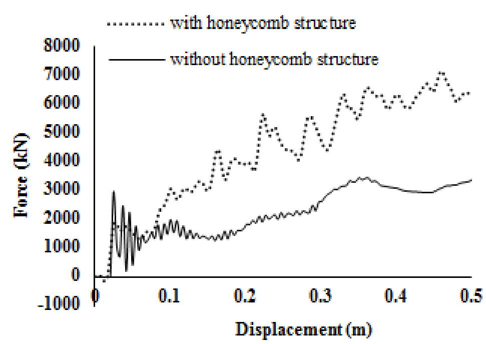

Figure 16. The force versus crushed displacement with and without honeycomb structure

5.3. HIC Criterion

The Head Injury Criterion (HIC) can be used to assess occupants' safety related to vehicles during collisions.

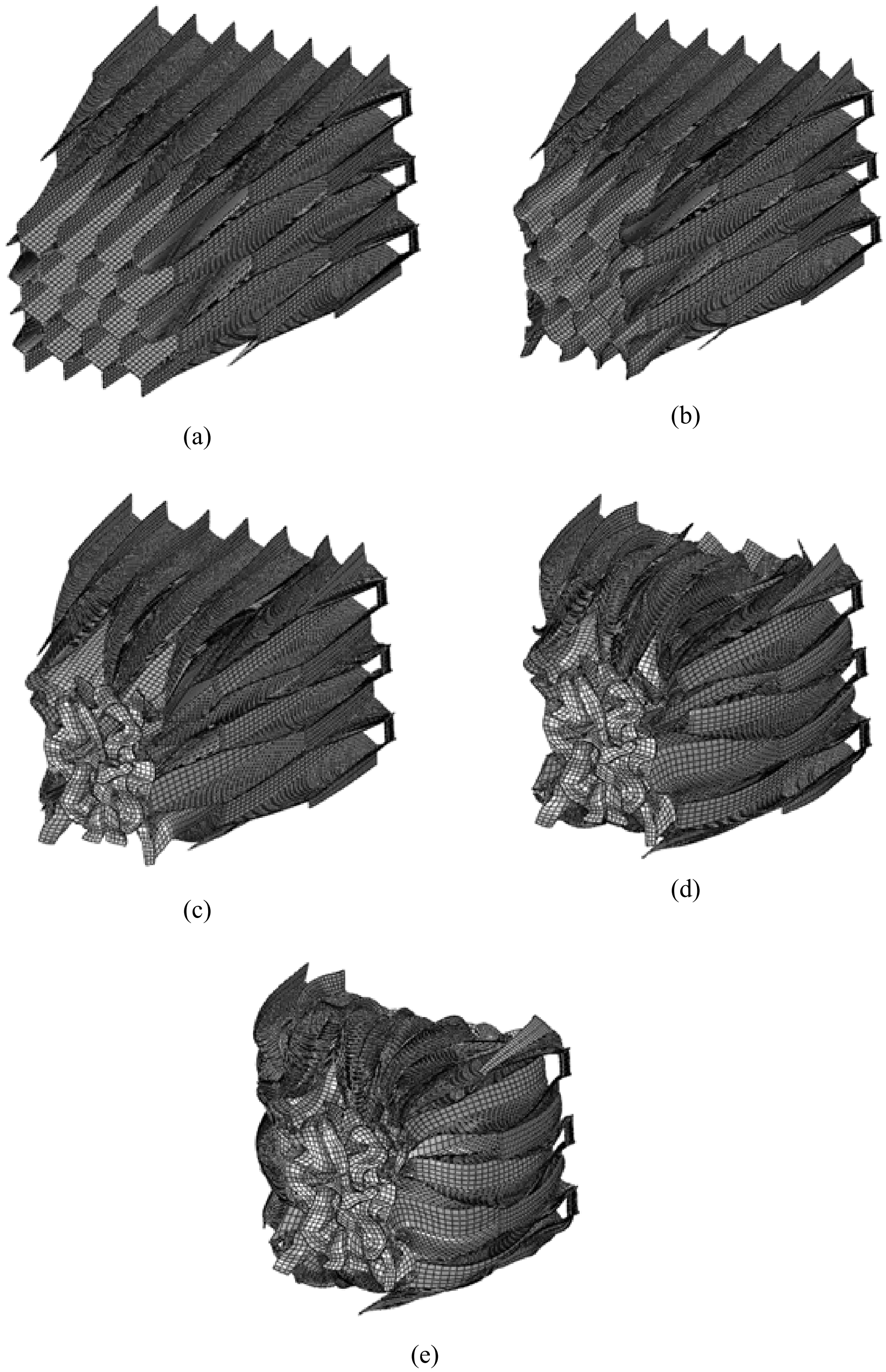

Figure 17. Performance of honeycomb structure against time spent in collision (a) 0 second (b) 0.0075 second (c) 0.015 second (d) 0.0225 second (e) 0.03 second

With this criterion it is tried to quantify the injury levels to a person's head when that person's head impacts some surface during a vehicle collision. Versace in 1971 proposed the following equation for calculating HIC [21]:

$$\mathrm{HIC} = (T_2 - T_1)\left\{\int_{T_1}^{T_2} \frac{A_v}{T_2 - T_1} dt\right\}^{2.5} \quad (4)$$

Where A_v is the dimensionless acceleration and $T_2 - T_1$ is the time interval that must not exceed 36ms. For the scenario of the locomotive collision in this research, the HIC criterion is calculated and the results are presented in Figure 18.

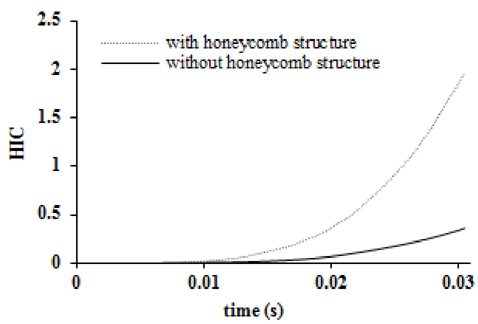

Figure 18. The HIC versus time with and without the use of honeycomb structure

The findings for this case is that the size of HIC is in a permissible range. It is far from its critical value for the collision of railway vehicles [22]. In this case, the lower size of HIC is due to the lower decelerating of train compared to the deceleration of the lighter vehicles such as automobiles during accidents. Figure 19 presents the rate of deceleration versus the crushed displacement during the collision.

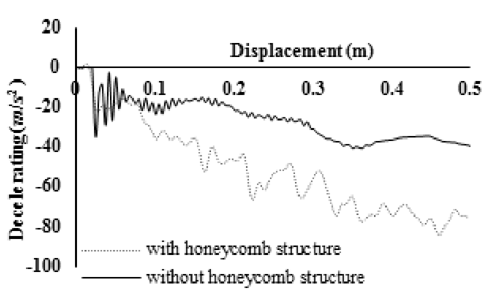

Figure 19. The train deceleration versus the crushed displacement during collision

It is clear that the size of the train deceleration is not excessive. This is due to the larger inertia of the train. It is concluded that the performance of the modified crash element with the inclusion of the honeycomb structure is acceptable.

6. Conclusions

The mechanical performance of the front end energy absorption mechanism of IrSa locomotive is investigated. The following results are achieved:

- The existing collision energy absorption mechanism of IrSa locomotive is susceptible to serious damages under certain circumstances.
- The metal sheet inside the crash element is thick. The intensity of the shear stresses at the corner of the segment is also high. The combination of these features causes rupture of the metal sheet at its corners that spreads into other areas. The simultaneous action of the metal sheet rupture and its folding can cause serious damages to the crash element during the collision.
- The numerical simulations predict that the energy of impact at the size of 474472 J can be endured by the energy absorption mechanism during the selected scenario of the collision. This is categorized as a large amount of energy that can cause serious damages to the locomotive. Therefore, some modifications to the design are essential.
- By inserting a design of a honeycomb structure inside the crash element the size of the collision energy absorption can increase to 74.6%. Meanwhile, the initial peak of the crash force decreases to 37%.
- With the inclusion of the honeycomb structure the size of the crash force increases. However, such an increase does not cause increase of the Head Injury Criterion (HIC) beyond its permissible levels. Hence, the proposed design for the crash element stays on the safe side.

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