Enhancing the safety and reliability for loading and unloading bulk storage bags and a new bulk feeder support design structure

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Abstract: Super bags are used to pack large and heavy bulk materials. They are durable; however they can be damaged by improper handling or misuse. Ensuring the safety of the operators who handle heavy bags is a main concern. The first objective is designing a backup safety frame to support the suspended bags by the hoist. The second objective is designing a spider bag support system compatible with the new frame and able to lift the super bag as required by Occupational Safety and Health Administration 1926.554 standard. Minimising weight and reducing cost were taken into consideration. The new frame and spider combined design mechanical properties were simulated using ANSYS™ software. The results showed the maximum deflection found at the spider was 1.78×10^{-3} m, while the maximum strain was 0.0006 for 250 MPa material yield stress. The maximum stress was 100 Mpa located at the hopper's base. The combined design safety factor was 2.503 and fatigue safety factor was 1.45. This study concluded the new frame and spider structure will achieve the desired objectives and meet the OSHA regulations.

Keywords: bulk bags safety; spider support; hoist safety; stress and fatigue.

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1 Introduction

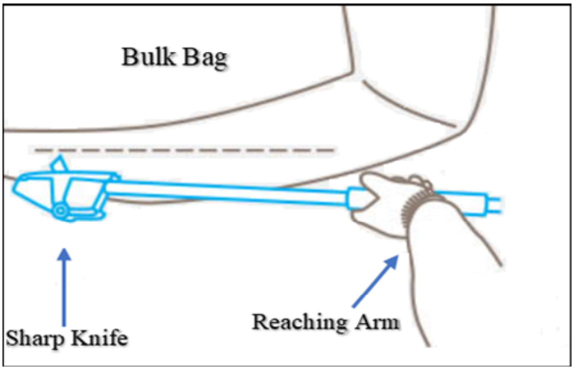
Large bags are highly durable and made of light weight and strong woven polypropylene material and are usually used to pack bulk materials in industries owed to their economic and ergonomic advantages in handling bulk material (Rosa, 2018). As a result of growing economy, the use of bulk backs is gaining more popularity in industries. The increased use of super bulk bags in different industries has saved operators time, reduced costs, and improved efficiency. In 2015 over 34 million bulk bags were used in the USA, which is a 20% increase from the previous year due to the growing economies of the manufacturing sector (Owens, 2018). But the increase usages of bulk bags have created a new class of safety issues.

Bulk bags are normally hoisted by their straps using a motor driven hoist on a rail to lift and position the bags over hoppers to dispense their contents. Injury risks for bulk bags rise due to improper handling or misuse (Podevyn, 2015). If the bulk bag was improperly overloaded or not properly supported, the weight will distribute unevenly on the frame, causing it to lean, bend, twist, topple, burst, rip off and fall over during loading and unloading operations (Owens, 2018). Therefore, safety factors of bulk bags need to be accounted for in any new back up design – usually rated from 5:1 to 6:1 for working loads (Brauer, 2016).

In addition, workers often have to reach under the bags to cut the bulk bag or untie the spout with a knife to discharge it, which introduces unnecessary risk (see Figure 1).

This hazardous operation could get the workers to be trapped or crushed under the bag and get injured or killed if the hoist suddenly fails (Carrington, 2019).

Figure 1 Reaching under commercial bag bulk to open it using sharp knife (see online version for colours)



Incidents due to the significant weight of bags can be catastrophic (Komol, 2020). Therefore, industries that use bulk bags and bulk waste bags (Gavade et al., 2021) for material handling need safe handling methods for their bags which could weigh more than 1 or 2 tons.

Safe work environment is a major concern for any administrations in industrial facility, thus, implementation of a new design is needed to prevent injuries, save human lives and save companies economic consequences resulting from the workers claims and medical treatments. The lifting hoist cannot be the only support for the bulk bags in the event that the hoist fails and drops the load, according to OSHA (2001) standard number 1926.554, which requires heavy-duty bulk bags have a supporting frame structure underneath with the capacity to safely hold the entire weight of the bag. The hoist lifts the heavy bags using a device known as a spider hanger with four arms, to hold each bag straps safely. The spider should rest on the top of the new frame and the new frame should be resting on the hopper rather than have the bag sit directly on the hopper and attached securely.

Heavy bulk bags will be refilled and continually placed on the proposed suspension system. Loading and unloading of the heavy bulk bags using lifting hoist creates reversing cyclic stress where the stress alternates between equal positive and negative peaks as sinusoidal pattern during each cycle of operation (Goggins et al., 2006). When a material part subjected to a reversing stress (*Sr*), it has been observed that the failure of the part occurs earlier after a number of stress reversals (*N*) even when the magnitude of *Sr* is below the material's yield strength. Generally, the higher the value of *Sr*, the lesser *N* needed for failure (Susmel, 2009).

Cyclic fluctuations in stress, strain and pressure cause a progressive degradation of a material (Kim, 2019), which leads to material fatigue and it is the most common source behind mechanical structural failures (Pippan and Hohenwarter, 2017). The mean stress effect plays an important role in the overall fatigue strength of engineering materials. In particular, under uniaxial fatigue loading, it is seen that fatigue damage increases as the applied tensile superimposed static stress increases (Mott et al., 2018).

The first objective of this paper is to design a backup safety frame that is able to support the super bag weight of one ton that is supported by spider and lifted by hoist with a minimum safety factor of 1.5 to meet ASME safety requirement (ASME, 2017). The second objective of this paper is to present a new lifting spider design that is compatible with backup frame and capable to safely support the bulk bag loads.

The strength of the hopper in use must be analysed to insure its capability to support the additional weight. Allowing plenty of room above the hoppers to move and to position the bag above the hopper without interference is also a design factor to be considered. As always, cost, efficiency and safety are an important factors in this design, therefore, the weight and different types of materials were considered to prevent failure and to reduce costs. ANSYS™ software would be used to simulate the mechanical behaviour of materials to estimate the stresses and strain forces and to estimate the material deformation (Wu, 2005).

Zero based load is when the load is varied between zero and the value of the load (i.e. from 0 to 445 N), another way of stating this is to call it an ‘on/off’ load (Budynas and Nisbett, 2014). The Goodman relation can be used to measure the relations between the mean and alternating stresses and the zero based loading was assumed due to the loading and unloading of the heavy bulk bag to evaluate the fatigue life of a material (Sutherland and Mandell, 2005).

2 Method

The bulk bag frame design consist four boxed tube steel uprights welded to the base with two support rails that the spider will rest on, welded on top to the uprights (D’Antimo et al., 2017). A boxed tube diagonal piece was welded to from the top corner of one of the up rights to the lower corner of the opposite upright in plane with the support (Landolfo et al., 2009; Shi et al., 2010). The same is done on the other side. These additional strengthening members not only provide additional strength, but also reduce the chance of the support structure buckling under loading.

Bag tilting is and important design criteria to allow the spider to move past the hopper centreline to free up space in between each hopper, these support rails were extended about 30 cm past the base to allow the bag to be tilted by placing the spider and bag further back on the supports (see Figure 2). A further design feature is the addition of non-slip rubber pads on top of the support rails to prevent sliding of the spider.

For the uprights, diagonals, and support rails were all fabricated with 10.16 × 7.62 × 0.48 cm ASTM A36 steel square tubing with a 7.62 × 7.62 × 0.95 cm angle base which rest over the hopper and secured by a maximum of 31.75 cm bolts to add more stability for the base of the hopper and the hopper’s flange (see Figure 3).

A new spider hanger was designed to work more efficiently with the newly backup safety frame. The new hanger design was based on the ‘H’ shape with the addition of four box tube sections welded at each of the tips of the ‘H’ parallel to the centre cross member. These sections allow the spider to sit on top of support without interfering with the straps or the uprights position support of the bulk bags. The bag support strap tabs were also welded to the top of the spider hander to keep the bag straps in place during usage. The middle of the ‘H’ design was recessed downward in order to allow more movement. The design of the spider is made of 7.62 × 10.16 × 0.8 cm and 10.16 × 10.16 × 0.48 cm structural tube steel as well as 0.8 cm plate steel (see Figure 4).

Figure 2 Final side support design (see online version for colours)

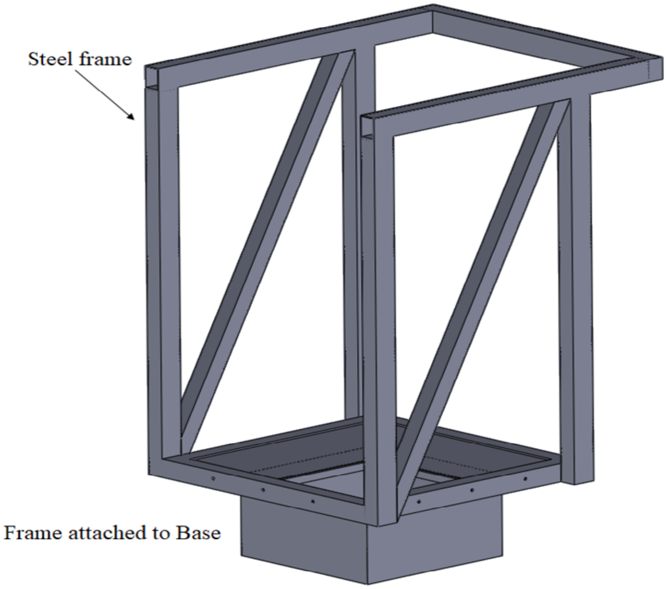
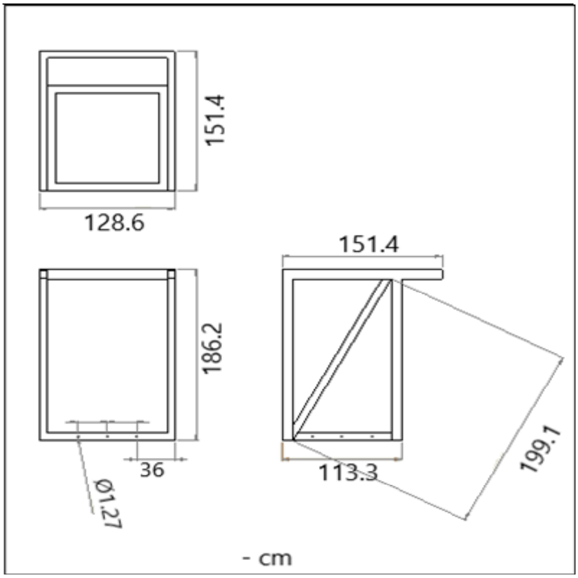


Figure 3 Final support frame design dimensions



The plate steel makes up the raising point fixed in the middle of the ‘H’ frame. The ‘H’ shape is made up of the 10.16 × 10.16 cm steel with the strap hooks being made of modified 10.16 × 10.16 cm section. The four outside pieces that will allow the spider to rest on the support rails are made of 7.62 × 10.16 × 0.48 cm structural steel and are made to overhang the support rails in an effort to boost safety during operation by making it easier for the operator to land the sider on the rails. Figure 5 illustrate the final spider-hopper assembly, and the newly designed spider holding a bag via the moving hoist.

Figure 4 Bag support structure (spider) dimensions (see online version for colours)

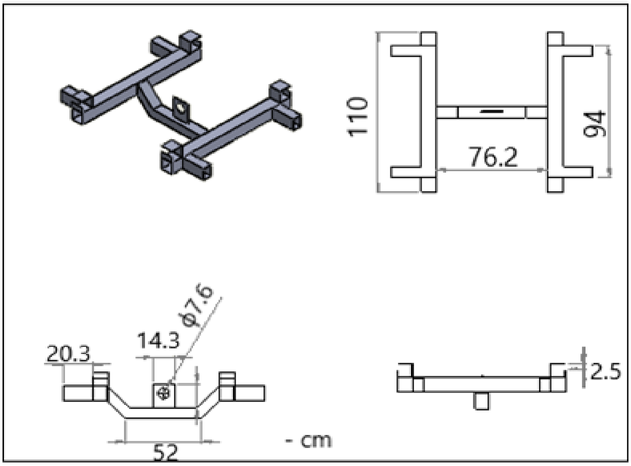
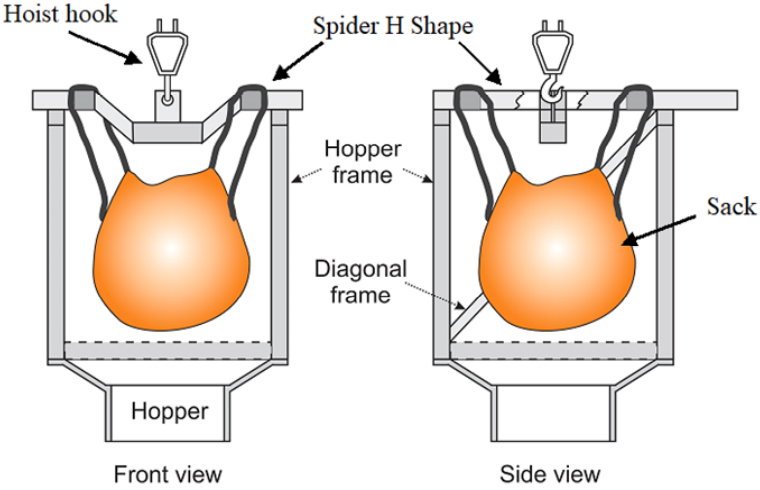


Figure 5 The hopper base with the spider resting on the top (see online version for colours)



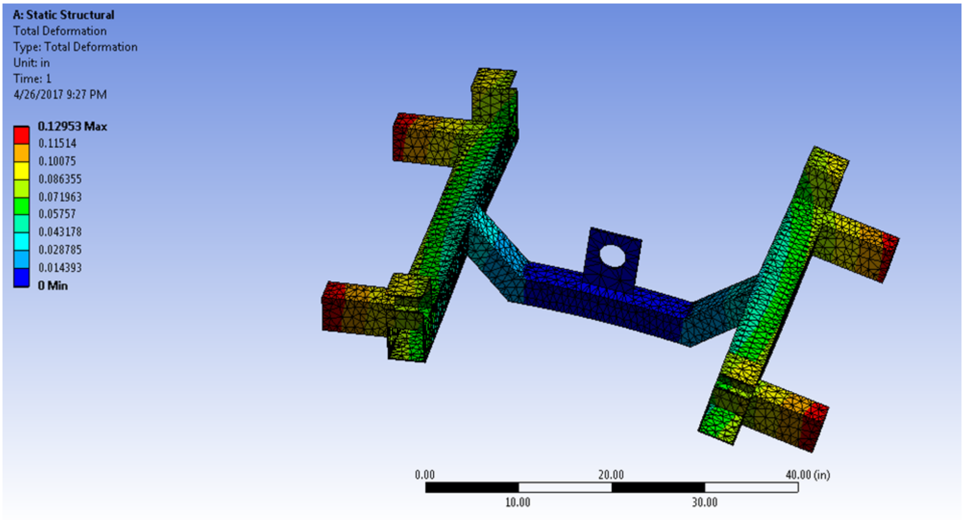
For the final frame design calculation, few assumptions were made. First, the bottom of the cone is static with respect to the rest of the structure. Second, a total force of 14,679 N was divided equally into four parts acting on the handles of the spider, and Goodman criteria was used for fatigue analysis and the maximum equivalent stress was used for stress analysis.

Each components on the newly designed backup system was simulated using ANSYS™ modelling software to measure deformation, strain, stress concentration and fatigue then based on the results the expected safety factor would be calculated for each component (Alkhaledi, 2015).

3 Results

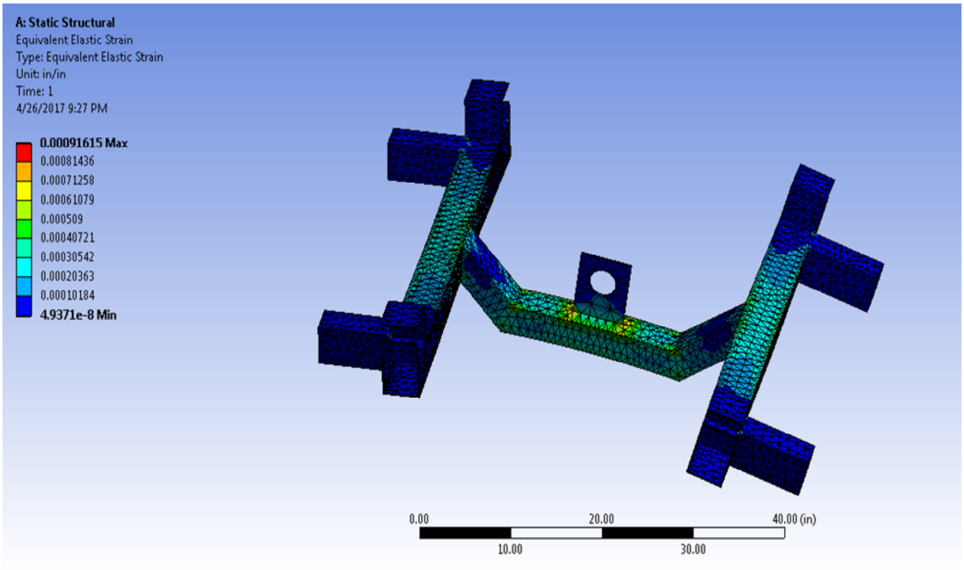
ANSYS™ modelling software results showed after applying a load of 14,679 N on the spider's straps. The maximum spider's deformation found was 3.29 × 10^{-3} m, which occurred at the protruding end of spider where the frame is attached (see Figure 6).

Figure 6 The maximum deformation for newly spider's design (see online version for colours)



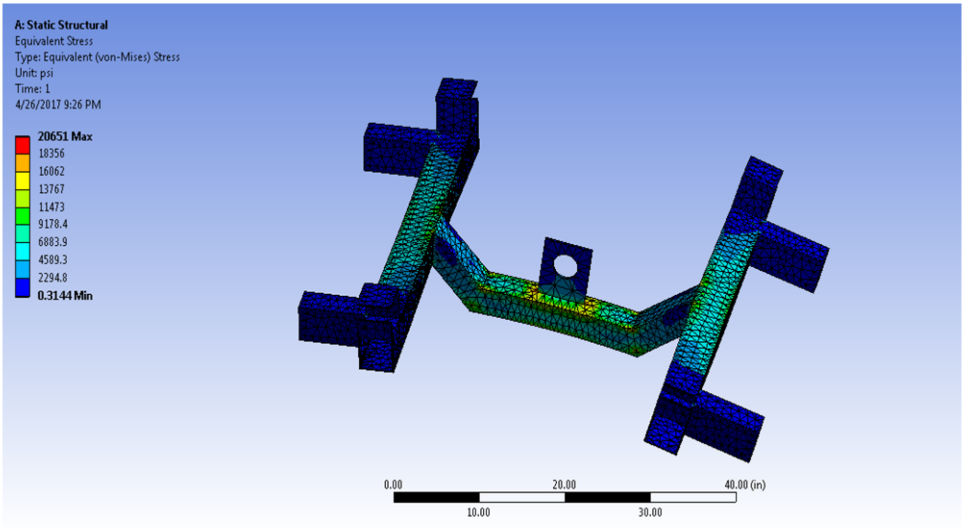
The maximum strain experienced by the spider was 0.00092, which is within the acceptable range of 0.005 (see Figure 7).

Figure 7 The strain for newly spider's design (see online version for colours)



The maximum stress concentration was 142.4 MPa which occurred around the middle part (see Figure 8). The yield stress was around 9,816 MPa for the materials used in this study.

Figure 8 Stress analysis for the new spider hanger design (see online version for colours)



The safety factor of 1.75 was found for spider stress concentration based on maximum equivalent stress and tensile yield per material (Figure 9). For the fatigue analysis, the minimum safety factor was 1.02 (see Figure 10).

Figure 9 The new spider's safety factor (see online version for colours)

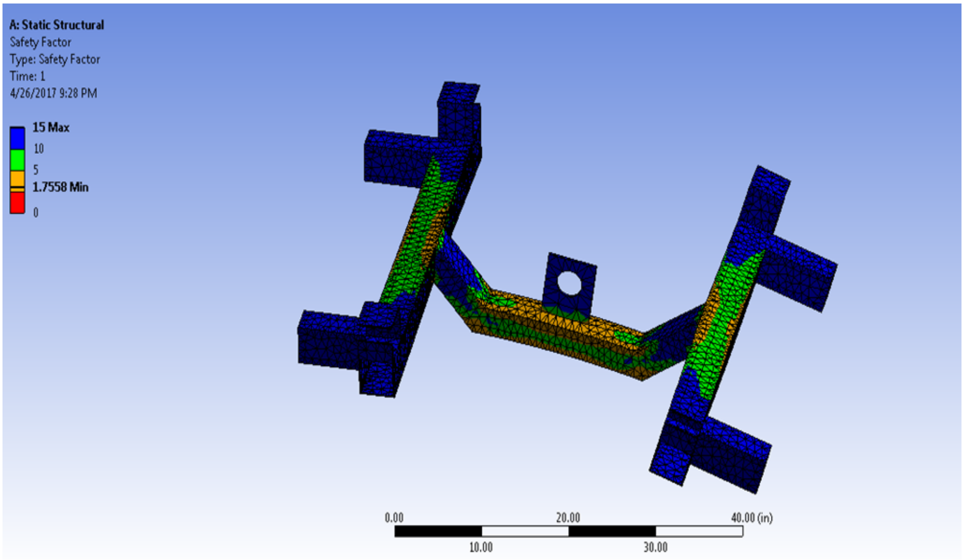
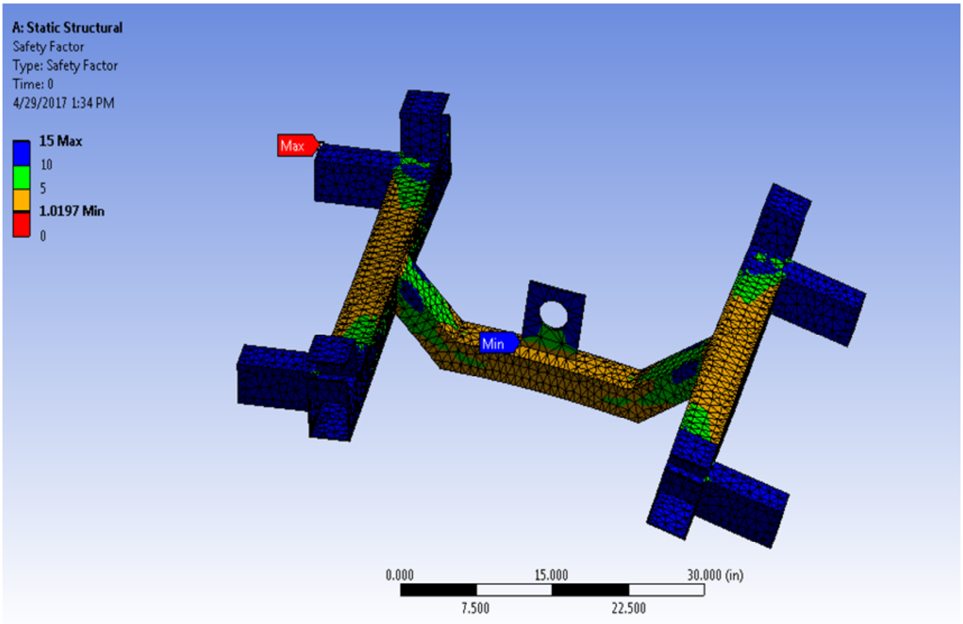


Figure 10 The fatigue analysis for the new spider (see online version for colours)



The hopper experiences a load of 29,358.3 N around the edges of the structure, the maximum total deformation was 0.3×10^{-3} m. The maximum deformation occurred at the back part towards the protruding end of the frame (see Figure 11). The Hopper maximum strain was 0.00087, which is within the acceptable range of 0.005 (Figure 12).

Figure 11 The hopper structure maximum deformation (see online version for colours)

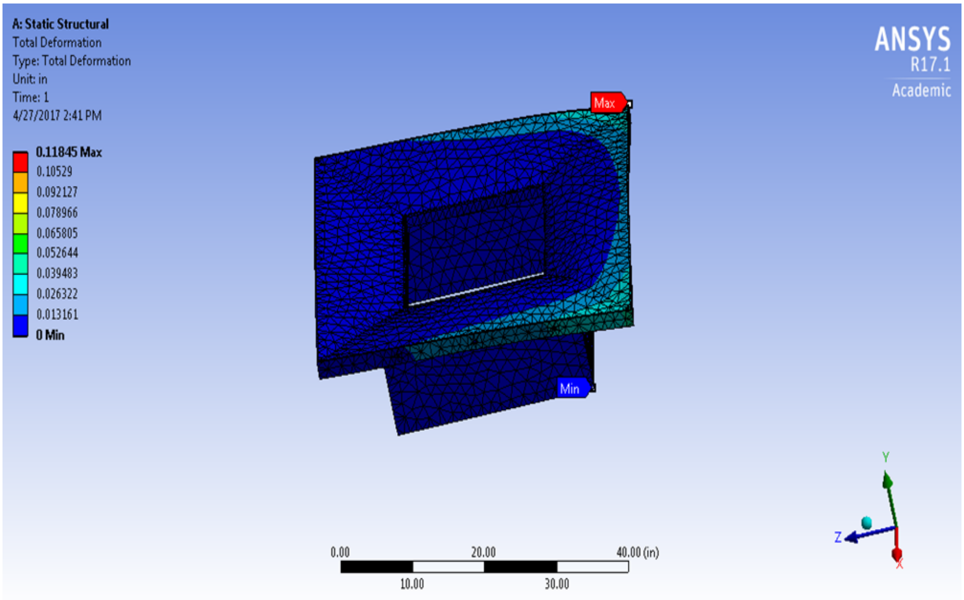
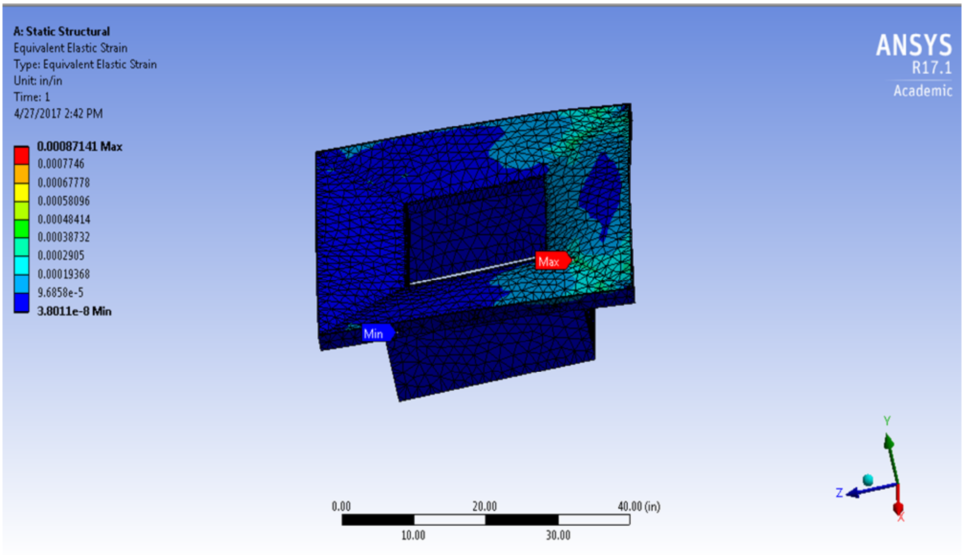
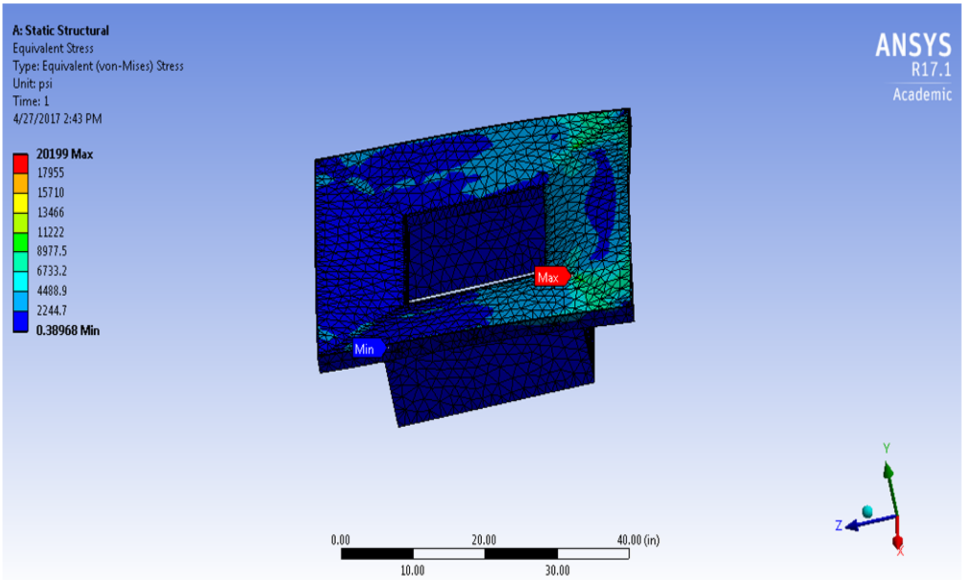


Figure 12 The hopper structure maximum strain (see online version for colours)



The hopper maximum stress of 139.3 MPa occurred at elongated end (see Figure 13). The material's yield stress was 250 MPa.

Figure 13 Existing hopper stress analysis (see online version for colours)



The safety factor of 1.8 was for the hopper stress concentration based on maximum equivalent stress and tensile yield per material (see Figure 14). Also for Hopper's fatigue analysis using Goodman mean stress theory, the minimum expected safety factor was 1.04 (see Figure 15).

Figure 14 The hopper's safety factor (see online version for colours)

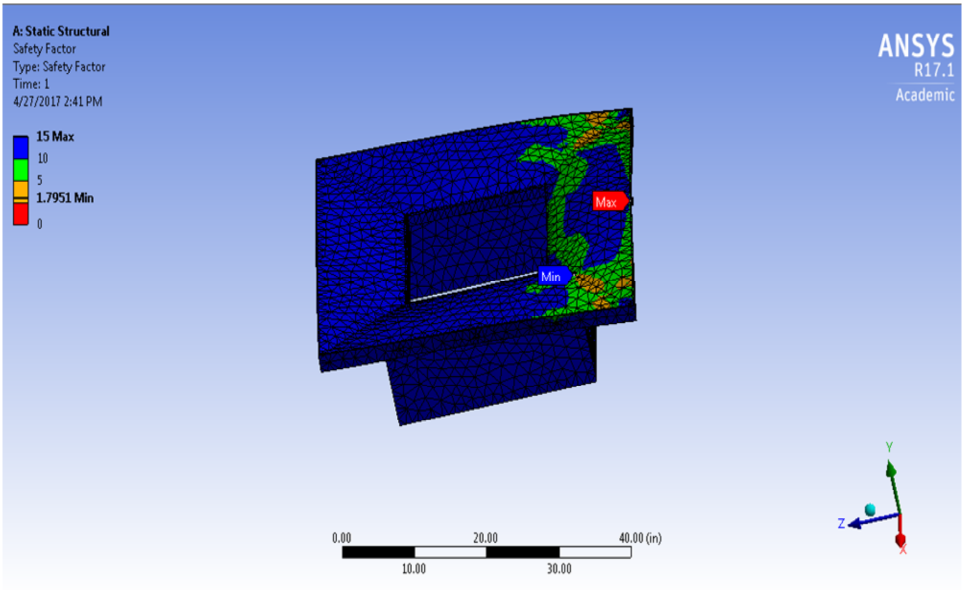
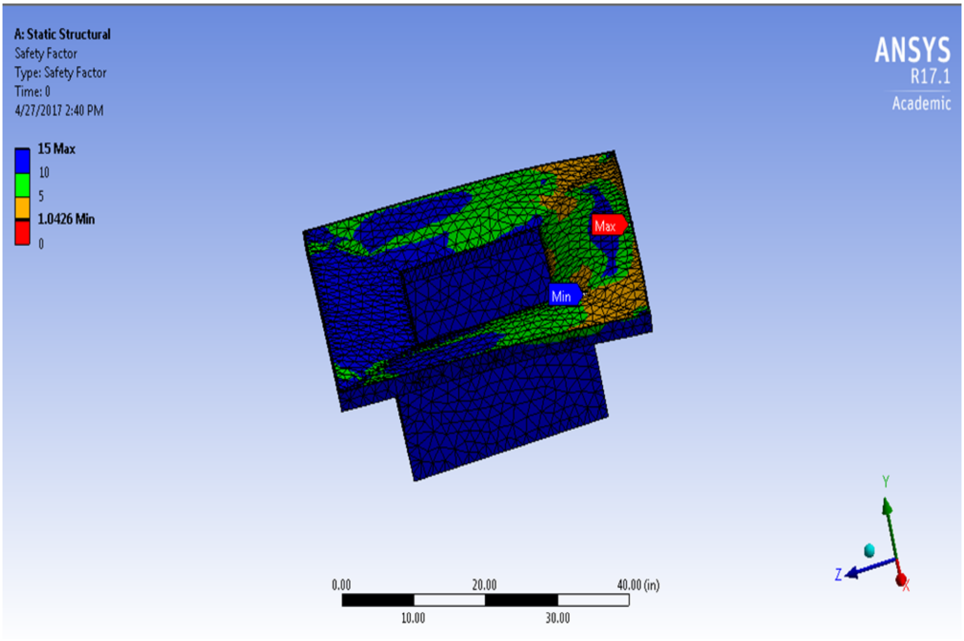
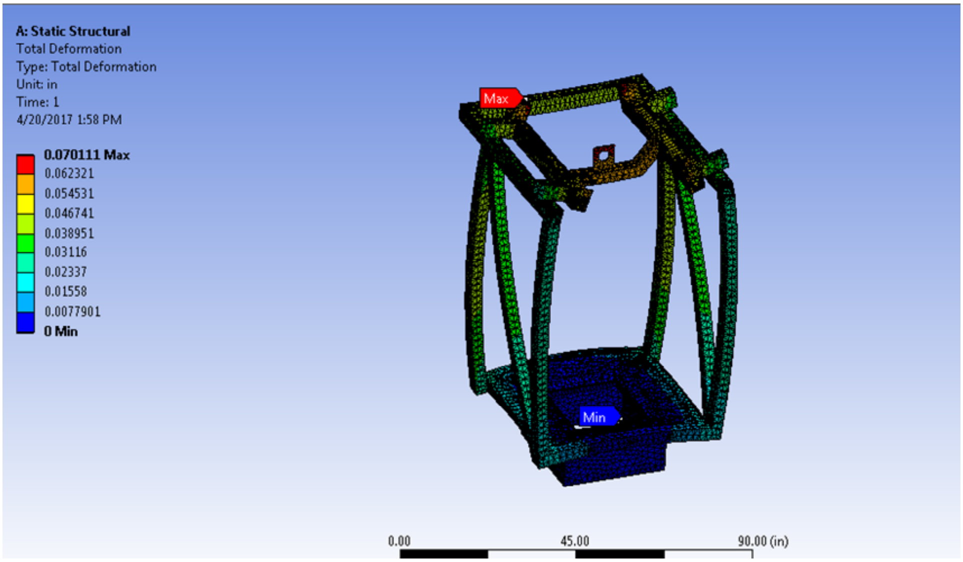


Figure 15 Hopper's fatigue analysis (see online version for colours)



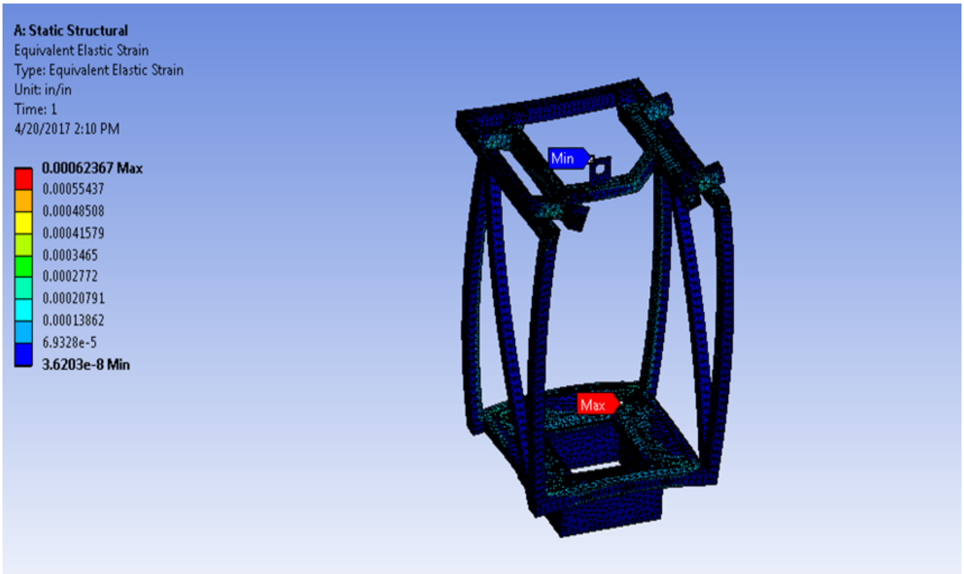
The total deflection was minimal compared to overall structure, the maximum deflection of 1.78 × 10^{-3} m happened at the spider (see Figure 16).

Figure 16 The maximum deflection for the three parts together (see online version for colours)



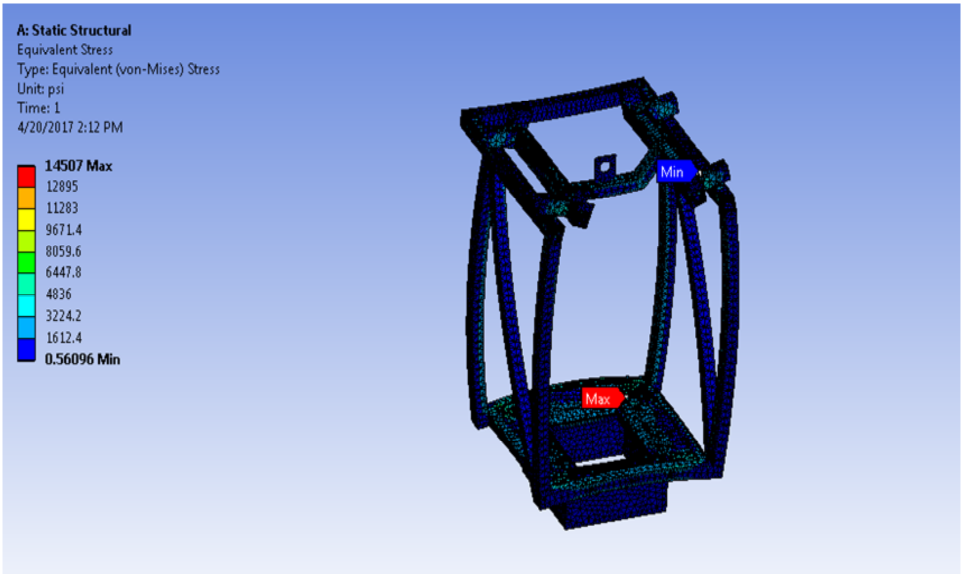
The maximum strain was 0.0006, well within an acceptable region. The maximum strain occurred at the hopper (see Figure 17).

Figure 17 The maximum strain for the three parts together (see online version for colours)



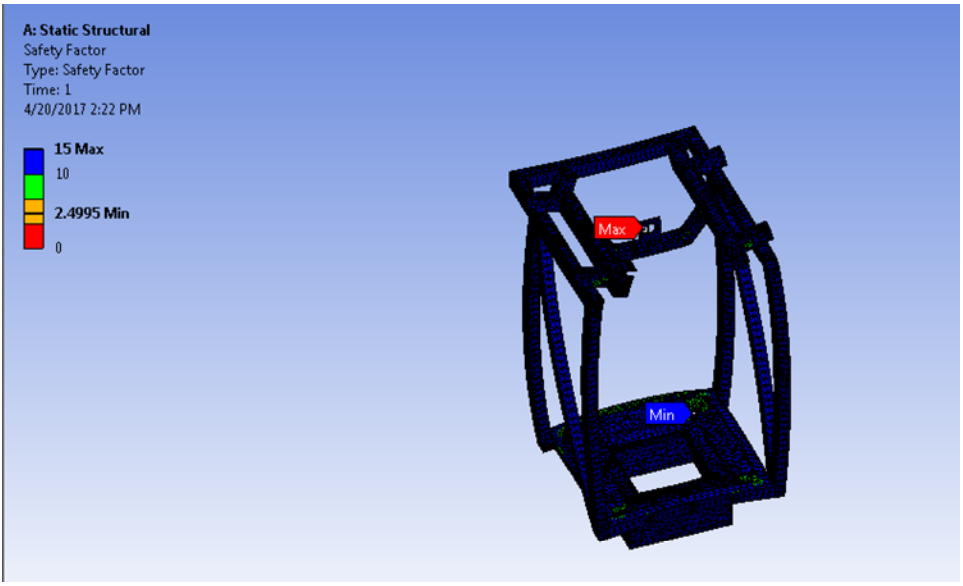
ASTM A36 material was selected for the new design with 250 MPa yield stress (ASTM, 2017). The maximum stress of the frame was 100 MPa located at the hopper base (Figure 18).

Figure 18 The stress concentration for the three parts together (see online version for colours)



Safety factor for stress concentration based on maximum equivalent stress and tensile yield per material was 2.503 (see Figure 19).

Figure 19 Safety factor for the three new parts together (see online version for colours)



For fatigue analysis, Goodman mean stress theory was used. The minimum safety factor was 1.45 (see Figure 20). The results for each component are summarised in Table 1.

Figure 20 Fatigue analysis for the three new parts together (see online version for colours)

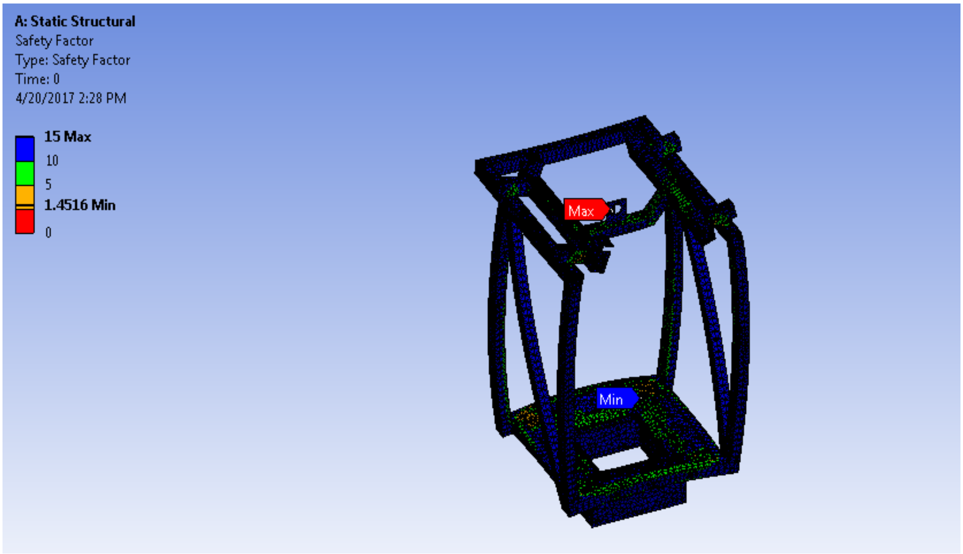


Table 1 ANSYS™ results summary

	Combined system	*Hopper*	*Spider*
Max deformation	1.78×10^{-3} m	3×10^{-3} m	3.29×10^{-3} m
Strain	0.0006	0.0087	0.00092
Max stress concentration	100 MPa	139.27 MPa	142.72 MPa
Safety factor based on Yield	2.50	1.80	1.757
Safety factor based on Fatigue	1.45	1.04	1.02

4 Discussion

Upon the use of ANSYS™ modelling software to measure different aspects such as deformation, strain and stress concentration, fatigue and safety factor for the newly designed safe suspension system. The following observations were noticed. The spider hanger part did take the entire load that was applied on it as required by the OSHA safety standard. The hopper is the base of the entire new design and any failure of the base would lead to the failure of the entire new design structure. The base showed positive results, therefore, the base was strong enough and did take the entire sequences of loads being applied as required by OSHA 1926.554 standard.

When the spider and the frame along with the hopper parts were combined together to form the new design, the combined structure were a concern in this study because failure of any part of the new design during loading could lead to failure of the entire structure (Helena and Knight, 2005), which may cause injuries, deaths or money losses due to damages and stopping the production. After the load was applied at the combined structure, the maximum deflection was found at the spider part 1.78×10^{-3} m, which is less than the deflection when the same load was applied at the spider hanger by itself 3.29

$\times 10^{-3}$ m. This shows a positive decrease in spider deflection by 46% when the spider was embedded with the overall structure of the new design.

For the hopper base part, after applying the same load, the hopper base experienced a deflection of 3×10^{-3} m, while when the load was applied at the combined structure, the maximum deflection was found to be less than 1.78×10^{-3} m. This is a good indication that the hopper deflection decreased even more than 40.6% when the total parts were combined together.

When the load was applied at the combined structure, the spider maximum strain was reduced from 0.00092 to 0.0006, which shows a decrease by 34.7%. Also the strain on the hopper base was enormously reduced by more than 93.1%. This happened because each part of the combined structure did take some amount of the applied load that leads to drop in strain.

Since the yield stress for the materials used in this design is 250 MPa, and after applying the loads, the maximum stress concentration for the new spider's design part was 142.72 Mpa and for the Hopper was 139.27 Mpa, on the other side, when the same load was applied on the combined design parts together, the maximum stress found at the hopper base was 100 Mpa, which shows a decrease in the yield stress by 28.2% for hopper base, and a decrease by more than 29.8% for the spider part. Based on yield stress analysis, the safety factor for the spider was 1.75 and for the Hopper was 1.8, however, when the three parts were combined together to form the final design the safety factor increased to 2.5, which means that the new combined design will be able to handle the applied load safely even if the applied load increased by two and half times.

For the spider's fatigue analysis, Goodman mean stress theory was used and zero based loading was assumed due to the loading and unloading of the super sack. The spider's minimum expected safety factor based on fatigue was 1.02, while the minimum expected safety factor was 1.45 for the combined design, which is a positive increase in the spider factor of safety by 42.1%. Moreover, for the Hopper's fatigue analysis, it showed similar increase in safety factor by at least 39.4%. The fatigue's safety factor increased because when the parts were combined together, the entire system handled the applied load (Coelho et al., 2006; Chung et al., 2005; Wong and Chung, 2020). Additionally, since the fatigue's safety factor is based on one million cycles, there is no danger of cyclic loading being a concern because it is unlikely for the bag system to reach a million cycles in its lifetime.

The total material cost of the newly designed prototype which includes rectangle tubes made of ASTM A36 steel and bolt connection that includes nuts and washers (Lee et al., 2014) can be estimated based on the market price. Cost should not be an issue when it comes to safety, the costs of welding, labour wages, costs of operation and equipment are factors that need to be considered, but they are difficult to estimate precisely because of many variables involved and various skills required (RSMeans, 2022).

When discharging the heavy bulk bag into the system workers should not reach under the bags to cut the bulk bag with sharp object. Therefore, to avoid unnecessary risk the spout should be untied and then bulk bag pulled into place to avoid contact between the bag and the operator.

5 Conclusions and recommendations

The heavy-duty bulk bag unloaders conceptual design was the main focus of this study since industries want a safer solution for their heavy suspended bags to insure they are not supported solely by the hoist in the event the hoist fails and drops the load causing major risks to workers.

The ANSYS™ simulation revealed that the newly tested backup frame and spider combination were reliable and stable to support the heavy bulk bag during loading and discharging process. Therefore, it is concluded that the new backup structure would achieve the desired objectives to meets the OSHA regulations.

The cost of investment in new bag backup support system for safer workplace environment is reasonable and justified. Fatal and non-fatal workplace incidents not only cause suffering for workers, but also cost businesses far too much money in workers' compensation, claims and medical treatments (CDC, 2015). Thus, the important benefit of the new backup safety frame is to reduce the pain and suffering of workers, and to decrease the societal cost (Alkhaledi et al., 2013).

6 Limitation

Although simulation is a good tool for development, it can't be the final tool for validation and demonstration. Therefore, future continuation of this research is recommended with experimental validation.

The design cost could be a limiting factor. Different materials have different cost, thus further studies with different material with higher yield strength could be utilised to boost the carrying loads and reduce cost.

Bulk bags materials may build up a static charge during loading and unloading process, the dust material may ignite and cause an explosion (Owens, 2018). Therefore, further safety studies are needed to prevent static charge build up and to control fugitive dust during discharging process of the bulk bag materials to prevent any dust fires or explosions.

Acknowledgements

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